INVESTIGATION OF LIGHTNING PROTECTION

A Thesis Submitted

In Partial Fulfillment of the Requirements

for the Degree of

MASTER OF TECHNOLOGY

by

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to the

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CERTIFICATE

It is certified that the work contained in the thesis titled "*Investigation of Lightning Protection*" by **Major Narendra Kumar Verma**, has been carried out under my supervision and this work has not been submitted elsewhere for a degree

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March, 1996.

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ABSTRACT

Name of Student: **Major Narendra Kumar Verma** Roll Number: 9410433

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Lightning has serious destructive effects on property, material and life. Most of the research work has been to improve the protective systems against lightning. In this thesis, results of experimental investigations in the laboratory :· for the protection of structures and power systems against Lightning strikes have been presented, that is :-

- To study the effect of shape and size of the Air Terminal of a lightning rod used for protection of structures against lightning.
- The effect of Atmospheric Pollution and corrosion on the performance of the Protective Spark Gaps used for the protection of insulator strings and bushings in Power Systems.

The present investigations of air terminals have been done in long air gaps in the range of a few meters to simulate the natural process of lightning strike as closely as possible. The effective performance of Point shape has been experimentally verified. Parameters like breakdown voltage, breakdown strength of air and the statistical time lag have been compared for different shapes of Air Terminals. The corelation of shorter statistical time lag and greater attraction to lightning have been studied. Experiments were performed with standard shape of lightning impulse voltage of negative polarity.

The effect of atmospheric pollution and corrosion of the protective spark gap electrodes on their performance have been studied by artificially subjecting different spark gap electrodes to pollution layers. The breakdown characteristics was studied using standard li impulse voltage of both polarity. Corrections for variation in atmospheric conditions have been applied to study the deterioration of the spark gap performance. In addition to the pollution layers, the electrodes were also subjected to sea water salt spray in a fog chamber for exposing them to corrosion. It was found that corrosion layer on the electrodes severely deteriorates the performance of the spark gap by increasing the withstand voltage level. On the other hand, thin volatile insulating polluting layer reduces the withstand level due to rupturing of the layer during partial discharge and availability of particles for preionisation and initiating the breakdown.

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I would be failing in my duty not to mention the whole hearted help and assistance provided in many ways by the officers and staff of UHV Research lab of CPRI at Hyderabad without which this work couldn't even have begun. My gratitude to Dr CS Lakshminarasimha to have allowed me to use the impulse generator facility to my hearts content in spite of busy commercial testing schedule. My sincere thanks to Dr. R S Shivakumara Aradhya and P Rangaswamy for their invaluable guidance and help in creating the required test setup for the investigations. I would also like to place on record the uncomplaining assistance given by V Ramu, K Devender Rao, P Ravishanker, Palni Reddy and Mathi Yob who spent countless cold wet nights with me to assist me in carrying out my investigations. I would like to apologize to the families at the CPRI Colony whose sleep I had disturbed by the countless explosions throughout the nights.

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In the end I wish to thank my wife Manju , son Siddharth and daughter Ritu for their loving attention, inspiration and unflinching support without which this work could not have been done.

Major Narendra Kumar Verma

March 1996

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LIST OF SYMBOLS

U_b	Breakdown voltage
U_i	Voltage at which partial discharge initiates
U_{b-0}	Impulse withstand level
U_{b-50}	Impulse voltage level with 50% breakdown probability
U_{b-100}	Impulse voltage level with 100% breakdown probability
$U_{b+/-}$	Positive/negative polarity breakdown voltage
U_{bk}	Breakdown voltage for kaolin coated electrode
U_{bcor}	Breakdown voltage for corroded electrode
U_{br}	Breakdown voltage for resin coated electrode
E_b	Electric field intensity in dielectric at breakdown
E_{bmax}	Maximum electric field intensity at breakdown
E_{bavg}	Average electric field intensity at breakdown
li	Lightning impulse voltage
si	Switching impulse voltage
d	Gap distance between electrodes
η	Degree of uniformity of electric field, Schwaiger factor
T_{cr}	Time to crest of the impulse voltage
T_s	Statistical time lag
T_b	Time to breakdown
T_p	Propagation time of breakdown
l_{rs}	Length of last return stroke step
r_s	Attractive distance
V_p	Protective voltage level of a surge arrester.
μs	Micro seconds
HV	High voltage
BIL	Base insulation level
PD	Partial discharge
H	Height
ϕ or Dia	Diameter

CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

1.1 Introduction

Lightning has been the nature's most spectacular and awesome phenomenon. The physics of lightning has evoked considerable interest for a long time. However the currently acceptable theory of lightning is of great interest as it acts as a window to the machinations of nature.

Lightning is a natural phenomenon which has always attracted interest of mankind. It is an electrical discharge which takes place from the clouds. Lightning has serious destructive effects on property, material and life. . Statistics show that losses due to lightning all over the World are vast. Studies have been made to provide adequate safety from lightning strokes. Lightning phenomenon is statistical in nature, which is very difficult to model and predict. Most of the work has therefore been done to improve the protective systems against lightning strokes.

One of the major concerns for the power system engineers is its destructive effects on the power systems. Probability of lightning striking the energized transmission lines is seen to be higher than objects on the ground around it due to an ionized zone in the vicinity. The area in which lightning may strike is defined as ' Attractive Area '. Protective systems are designed in a way to attract Lightning and provide a desired protective zone around it.

The design of Lightning protection is a vast area of research and plenty of work has been done in this field. Work has been done on the shape and size of the Air Terminals of lightning conductor to provide greater attraction for the Lightning. According to Uman /1/

" *It is the most scariest and the most spectacular thing I know* "

It could be of different length having range from cms to kms through the air propagating at approximately 15 cm/μ secs , nearly half the speed of light. This high speed makes it impossible to see with naked eyes that , a bolt is also originating from the ground up towards the clouds. At that moment the temperature of the core of the discharge channel goes as high as 28,000 ^{o}C (Four times the Sun's surface temperature).

Although 3/4th part of its energy is consumed as heat, enough remains to deliver a full 125 million volts of electric potential of the clouds. Fallen on a tree , it burns and burst it apart. Fallen on a house may create a situation as if hit by a few hundred pounds bomb.

The frequency of lightning strokes is estimated to be hundred per sec, that makes it eight million per day. No one has a fool proof method of protection. Most of us fear lightning and that is due to the disaster and havoc it creates. It ignites fires in the forests and accounts for millions of rupees worth of property every year besides killing large number of living beings. It is one of the major cause of failure of power supply.

Thus it needs no great imagination to visualize the destructive effect of lightning on structures and power systems.

1.2 Protection of Structures

The invention and development of the lightning rod in 1850 AD by Benjamin Franklin can be called as the first scientific study on lightning which led to the wide acceptance of the lightning protection . He wrote that

" *Pointed rod erected on buildings and communicating with moist earth , would either prevent a stroke or will conduct it so that the building is safe " /1/.* (see fig 1.1)).

It is in the latter manner that lightning rod actually works . Lightning rods were first used for protective purposes in 1752 in France and in the same year in the USA. Even today Franklin's method is used to protect structures.

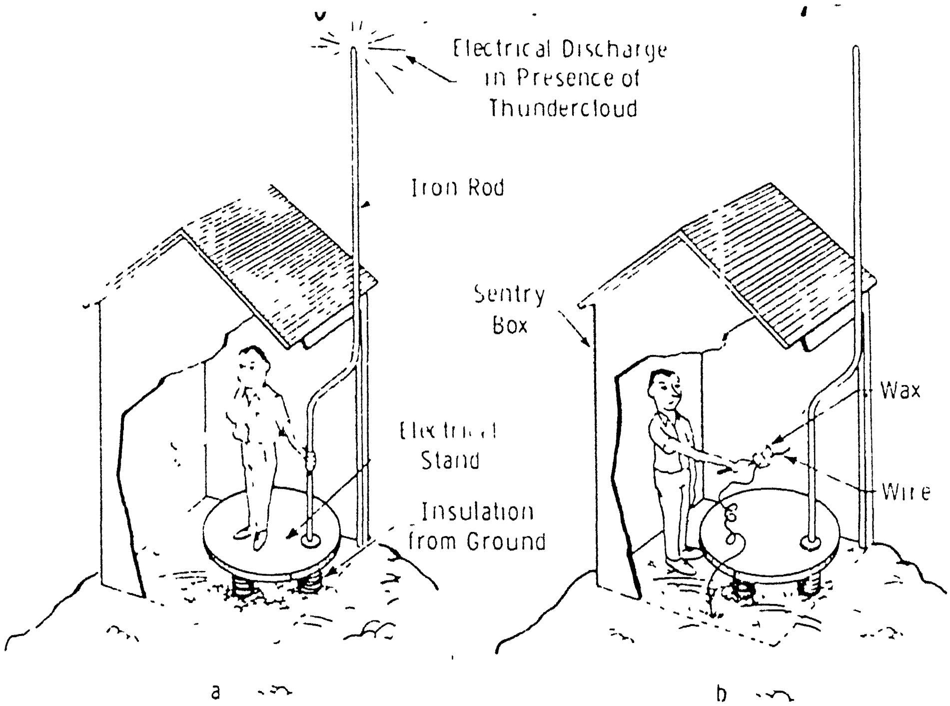


Fig. 1.1 Franklin's original experiment to show that thunderclouds are electrified (a) Man on electrical stand holds iron rod with one hand and obtains an electrical discharge between the other hand and ground (b) Man on ground draws sparks between iron rod and a grounded wire held by an insulating wax handle Adapted from Uman (1971)

1.3 Lightning Rods

The post-Franklin period may be taken to extend over almost two centuries during which little progress was made. It may, in fact, be said that few new problems were raised which had not been mentioned in one form or the other by the Father of the lightning rod himself. The question on which possibly the most misplaced ingenuity was expended was the famous controversy of " Blunt versus Points" for the tips of the lightning rods. Lengthy investigations were also undertaken to determine the conductivity of different metals in the erroneous belief that minimum resistance of the

lightning conductors would contribute materially to their effectiveness For the same reason, the tips of the rods were gilded or even made of Platinum (Lodge ,1892). The ımportance of a good earth connection was recognized early on as a result of some notable failures causing internal side flashing

On a more theoretical level two problems attracted wide attention. The first was the question of whether a lightning rod was capable of discharging a thunder cloud so effectively as to prevent a strike? This hope is now known to be largely illusory. The second is the protective zone of a lightning rod and this is examined briefly in the following paragraphs.

1.3.1 Protective Zone of a Lightning Conductor

The attractive range of a lightning rod was first questioned by a french scientist in 1779 after a powder magazıne in Purfleet near London was slightly damaged by lightning . The ratio d/h is also referred as the protective ratio where d is the horizontal distance from the base of the lightning rod and h is the height of the lightning rod from ground (see Fig 1.2 (a)).

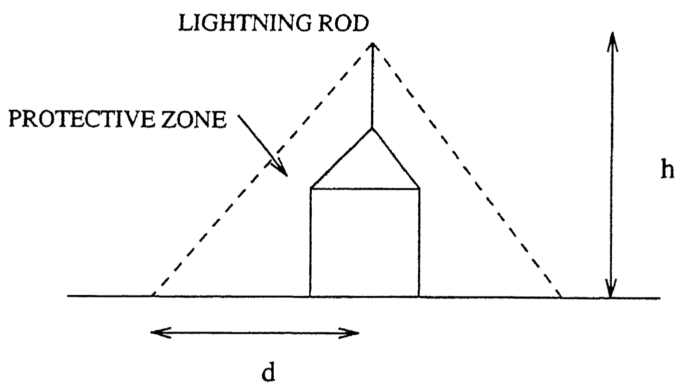


FIG 1.2 (a) PROTECTIVE RATIO D/H

There have been wide discrepancies in the Protective Zone as reported by different literatures. This can be seen in Fig 1.2 (b) .

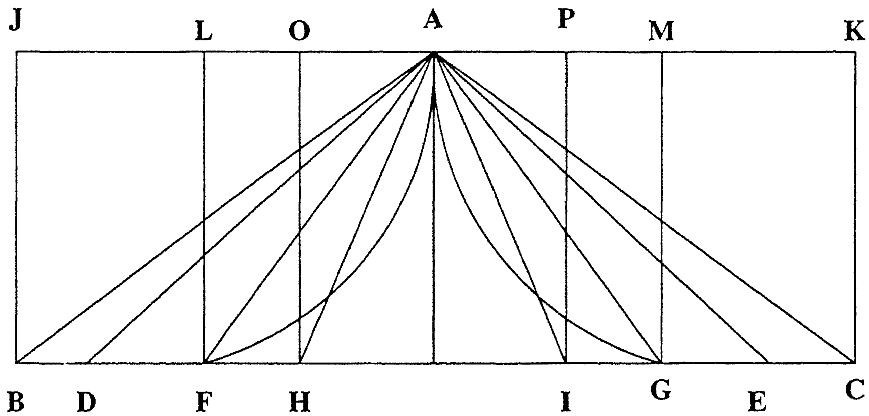


FIG 1.2 (b) ZONES OF PROTECTION AS REPORTED BY DIFFERENT AUTHORS

JBCK, GAY LUSAC (1823) , BAC, DE FONVILLE (1874) , DAE, PARIS COMMISSION (1875) , LFGM, CHAPMAN (1875) , FAG, ADAMS (1881) , OHIP, HYPOTHESIS, FAG, PEERCE (1881) HAI, MELSON

The distance from the tip of the downward leader channel to the ground objects that can be hit by lightning is called the striking distance. The striking distance is statistically strongly related to the amplitude of the lightning current as can be seen in Fig 1.3 ./2/.

1.3.1.1 Geometrical Approach (Rolling Sphere Method)

The geometrical solution of the problem of the protective zone is based on the concept that, at a certain point of its development, lightning will strike a lightning conductor in preference to earth if that constitutes the shortest path. The distance over which such strike will occur can be calculated by simple geometry. This thought had already occurred to Franklin (1776) who called this height the "Striking Distance", a term which is retained throughout this work.

The first person to use this approach seems to have been Preece (1880) who examined the electric field distribution around a vertical lightning rod. He concluded (without our present knowledge of leader stroke) that

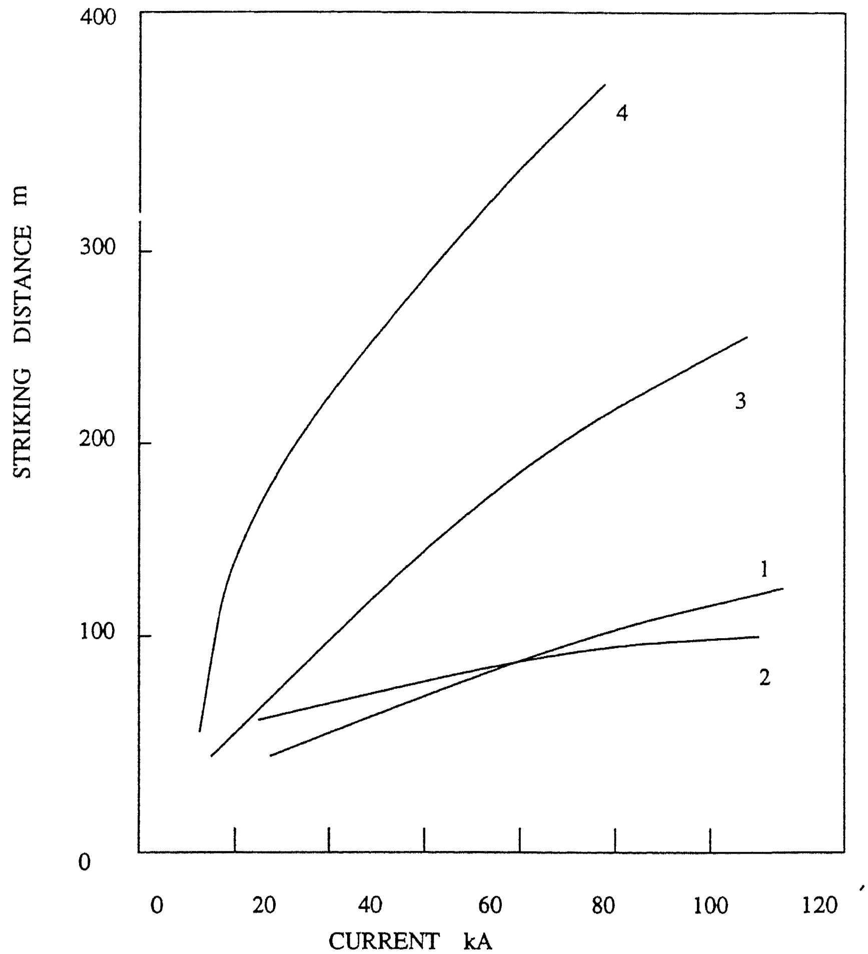


FIG 1.3 VARIATION OF STRIKING DISTANCE WITH LIGHTNING CURRENT

CURVE 1 · GOLDE, 1945 , CURVE 2 WAGNER, 1963 ; CURVE 3 . LOVE, 1973 , CURVE 4 : RUHLING, 1972,

lightning could strike the tip of a vertical rod horizontally from a height above ground which equalled the height of the Rod. He thus concluded:

"Hence a lightning rod protects a conic space whose height is the length of the rod, base is a circle having its radius equal to the height of the Rod, and the side is the quadrant of a circle whose radius is equal to the height of the Rod."

This protective zone is indicated in Fig 1.2 (b) by the cone AFG.

Another important condition for the lightning to strike is that the length of the last stretch of the stepped leader should be equal to or smaller than the length of the return stroke step (l_{rs}) of the original leader as shown in Fig 1.4 (a).

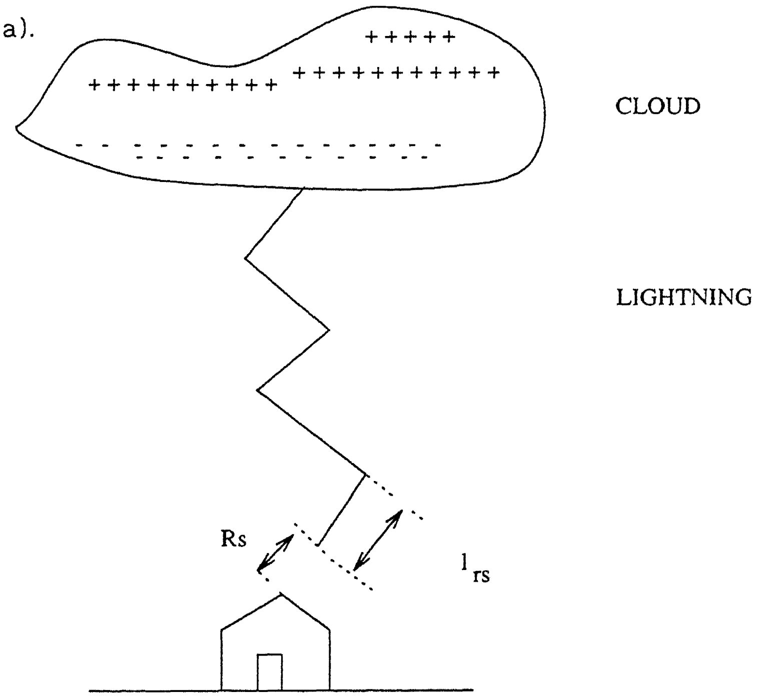


FIG 1.4 (a) LIGHTNING DISCHARGE WITH RETURN STROKE

For the construction of Protective zone a more practical method is to roll a sphere of radius r_s over the objects to be protected in order to provide a three dimensional sense of protective zone as shown in Fig 1.4 (b). This has been attempted to be experimentally verified in the laboratory by Sawhney /4/.

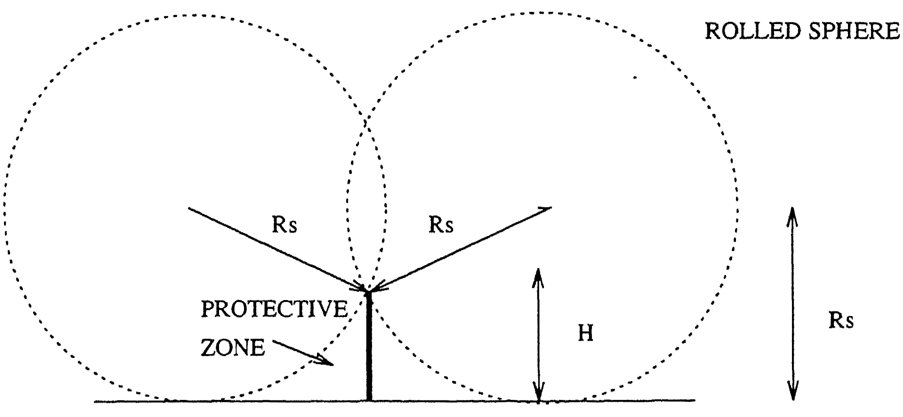


FIG 1.4 (b) CONSTRUCTION OF ZONE OF PROTECTION USING

1.3.2 Shape of the Tip of the Lightning Conductor (Air Termination)

As mentioned earlier the shape of the air termination has been in considerable controversy in the previous century. However, there existed no facilities to compare various shapes by artificially simulating lightning strike in the laboratory in the good old days. In fact, even the standards on lightning protection are silent on the best shape of the air termination. The IS.2309:1989 on Protection of buildings and allied structures against lightning is also silent about it /5/. No scientific research publication in this field could be found from the literature.

In a recent experimental work done by R Sawhney at IIT Kanpur /4/ it was observed that probability of strikes increased as the surface area of the air terminal was increased. In fact the most suitable shape for the air terminal is recommended in the form of a inverted cup. These findings are almost revolutionary in nature as they shake the existing belief that Point is the best. Since the experimental work had been performed indoors under a maximum gap distance of 15 cms, further work on longer gap distances was needed to validate the findings before they could be accepted as correctly simulating a lightning strike on a lightning rod.

Since the length of the last step of the downward leader and the return stroke is in several meters only experiments performed in gap lengths of several meters could correctly give an estimate to the best shape of the air termination and come close to artificially simulating a very complex natural phenomenon .

One of the object of this work is to investigate on longer gaps (in meters) the effect of the shape of the air termination on the performance of the lightning rod and if possible select the most suitable shape of the air terminal. Since the facility of HV lab at IIT Kanpur has the limitation of equipment to generate High Impulse Voltage of the magnitude needed to perform the experiments in meter gap lengths, the investigations were

performed at UHV Research Lab of CPRI at Hyderabad which has a 5 MV outdoor Impulse generator.

1.4 Lightning Strike on Power Systems and its Protection

Lightning activity around electrical transmission and distribution systems is the single greatest cause of line outages and system component losses. The electrical utility industry has expended much time and money in trying to reduce these outages and related losses of equipment. The efforts have been concentrated on trying to investigate the angle of protection of the ground wire, investigating the flashover voltage of the insulators, reducing the grounding resistance and developing various forms of surge arrestor technologies. These factors have been explored, simplified and cost optimized, resulting in some improved performance. Yet lightning related outages persist.

1.4.1 Overvoltages due to Lightning Strike

Lightning poses a great threat by generating transient overvoltages of very high magnitude on the power system. Overvoltages can be produced in one of the following ways:-

-Due to direct strokes

-Due to induced lightning

-Due to back flashover

Each of the above are briefly described in the succeeding paragraphs.

1.4.1.1 Due to Direct Strokes.

When a lightning directly hits a transmission line it injects an impulse current of very high magnitude, typically 10-100 kA of crest magnitude into the line. This current in the steep fronted wave shape travels in both the direction generating a steep fronted voltage waveform due to the surge impedance of the line. This wave travels throughout the system until it is attenuated fully by the protective devices like

protective spark gaps and the lightning (surge) arrestors. Failure of these devices can cause insulation failure of the insulator strings, bushings and the transformer windings.

1.4.1.2 Due to Induced Lightning

The 'Induced lightning' occurs in the following way. When a thunder storm generates negative charge at its ground end, positive charges are induced on the earthed objects, including transmission lines and towers. Normally one would expect transmission lines to be unaffected because it is insulated by string insulators. However, because of the high gradients involved, the positive charges leak from the tower along the insulator surface to the transmission lines. This process takes a long time, of the order of tens of minutes. When the thunder cloud discharges to some object (other than the line) the transmission line is suddenly left with a huge concentration of positive charge which cannot leak away suddenly and therefore resulting in overvoltages known as Induced overvoltages./24/

1.4.1.3 Due to Back Flashover

When a lightning directly strikes on a tower, carrying huge transient currents and if the tower footing resistance is considerable, the potential of the tower may rise steeply with respect to the line. Consequently the insulator string may flashover. This is known as Back Flashover./24/

1.4.2 Effect of System Voltage

There appears to be definite inverse relationship between the line voltage and the lightning related outage rate. The relationship is evidently created by the variation in potential difference between the line voltage and the transient overvoltage generated by the lightning strike. Unfortunately the relationship is somewhat obscured by the variations in the supporting structure grounding resistance, the surge arrestor deployment and the insulators.

The relationship work was taken up by Dr R H Golde /6/ of the UK. In

that situation the number of lightning days per year, also referred to as Keraunic number was only 9 whereas in India it varies up to 190.

Dr Golde's data illustrates two important points: First, the trip out rate for a 11 kV system is 10 time that of the 132 kV system even though they were in the same storm area ; second, trip out rates vary significantly between systems and depends on factors such as route, grounding resistance of support structures, arrestor configurations and insulators in use. Similar data was provided by Georgia Power company. Fig 1.5. gives the correlation of lightning related outages and the system voltage.

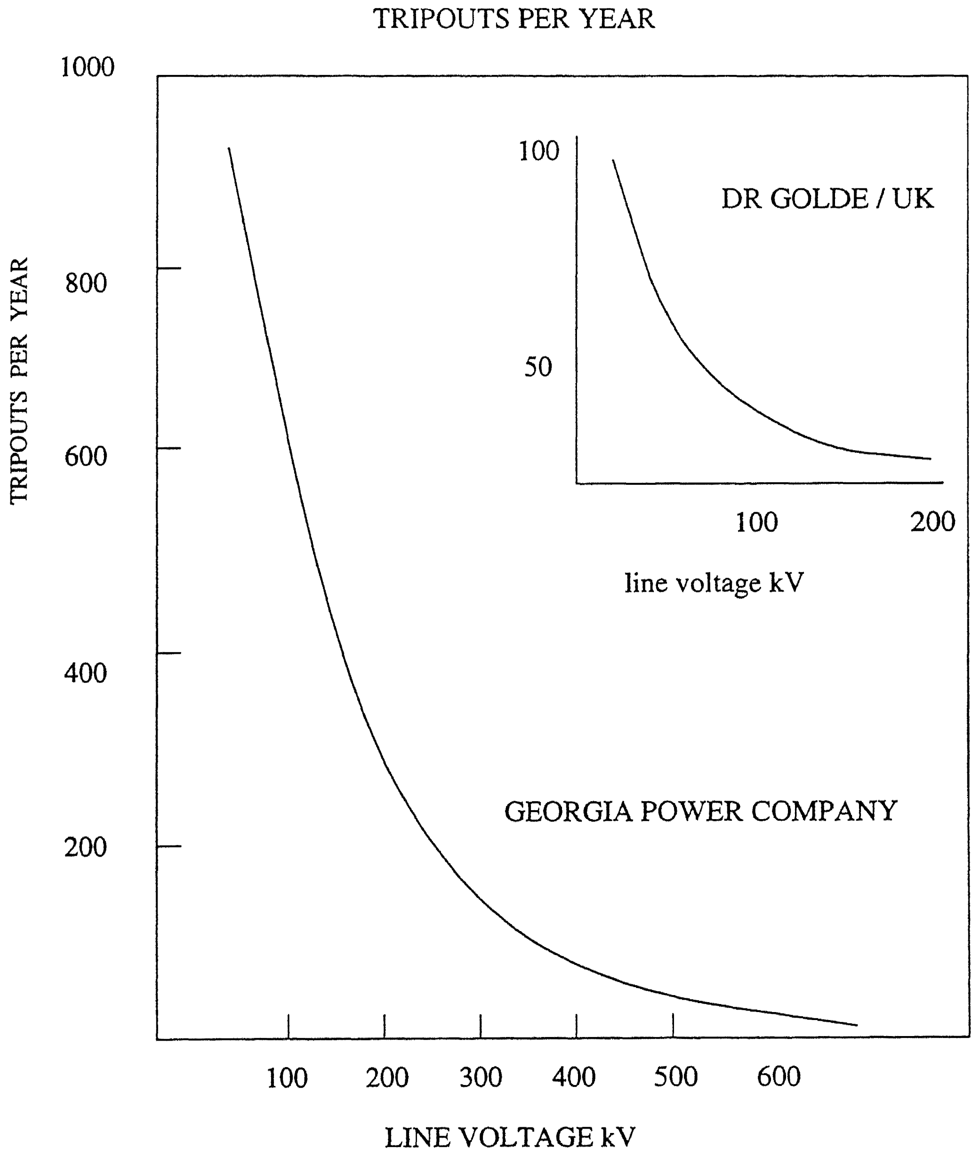


FIG 1.5 CORRELATION OF LIGHTNING RELATED TRIPS WITH SYSTEM VOLTAGE

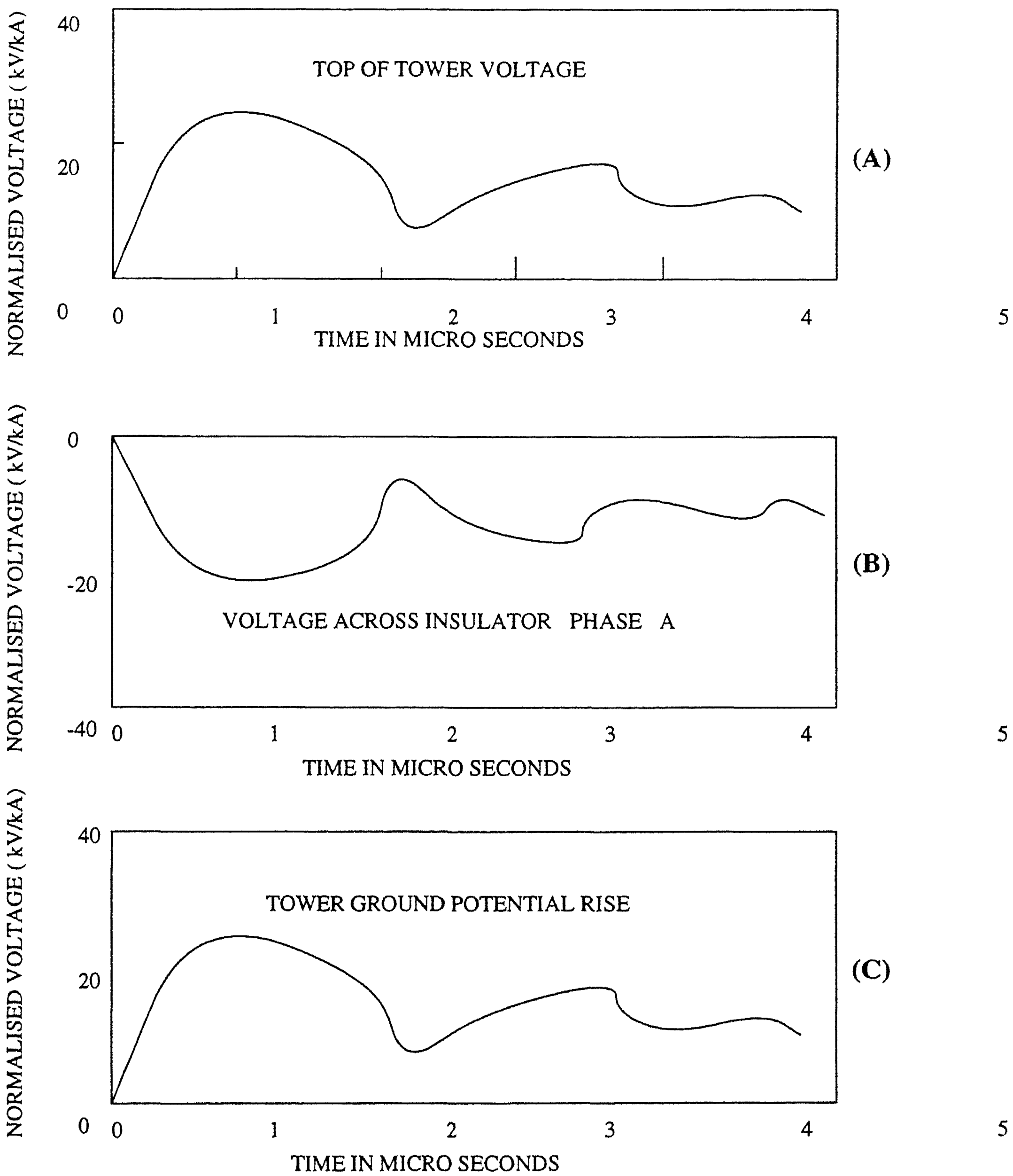


FIG 1.6 TYPICAL LIGHTNING OVER VOLTAGES ON A TRANSMISSION LINE

The lower trip out rate for higher system voltages is also due to the fact that these systems have higher Base Insulation Level (BIL) to withstand higher dynamic overvoltages produced due to switching which can be more damaging than the lightning strikes

From a qualitative perspective, higher voltage lines collect many times the number of strikes as the lower voltage lines because of the higher elevation factor (height of line and tower), though higher BIL results in fewer trip outs. Fig 1.6 shows typical overvoltages on a transmission line due to a lightning strike. /19/

1.4.3 Overvoltage Protection

There are a number of methods used to protect power system from damage caused by a lightning strike. Normally flashover cause temporary power outage due to temporary tripping of the equipment at which flashover occurred and the system is restored by the subsequent reclosing operation. Any solid insulation breakdown however leads to permanent outages. The equipment needs to be repaired/replaced before the system can be restored. This can be very expensive in terms of time and money. Therefore all efforts are made to avoid outages due to insulation failures of equipment.

1.4.3.1 Overvoltage Protective Devices

Electric Power Systems must be protected against overvoltages to avoid insulation failures and subsequent faults. For this purpose overvoltage protective devices are deployed. The principle of over voltage protection with help of a protective device is shown in Fig 1.7. /23/ .

This indicates that device should not allow the voltage to exceed the value V_p . V_p is referred to be as the protection level. Unfortunately this ideal characteristics cannot be achieved in reality.

Historically , the first overvoltage protection device has been a

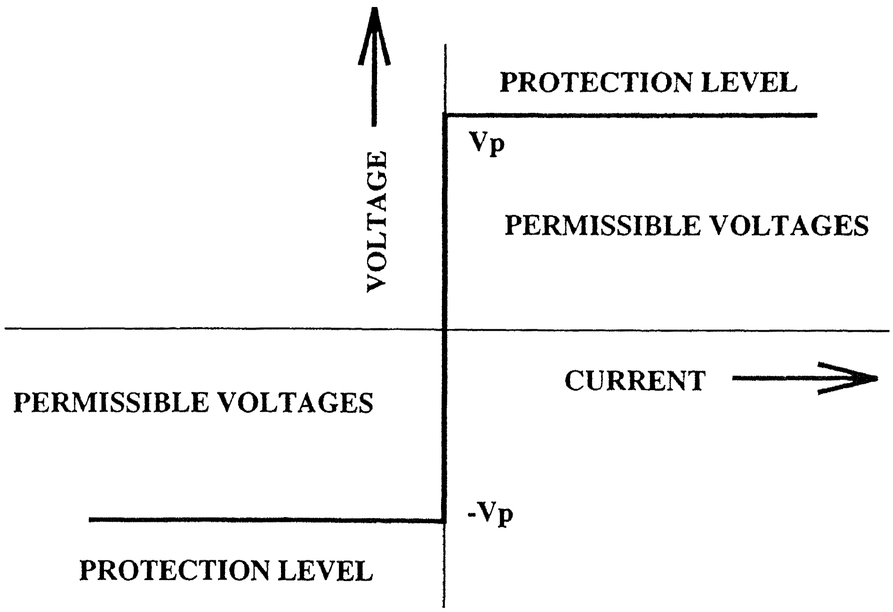


FIG 1.7 CHARACTERISTICS OF AN IDEAL OVERVOLTAGE PROTECTIVE DEVICE

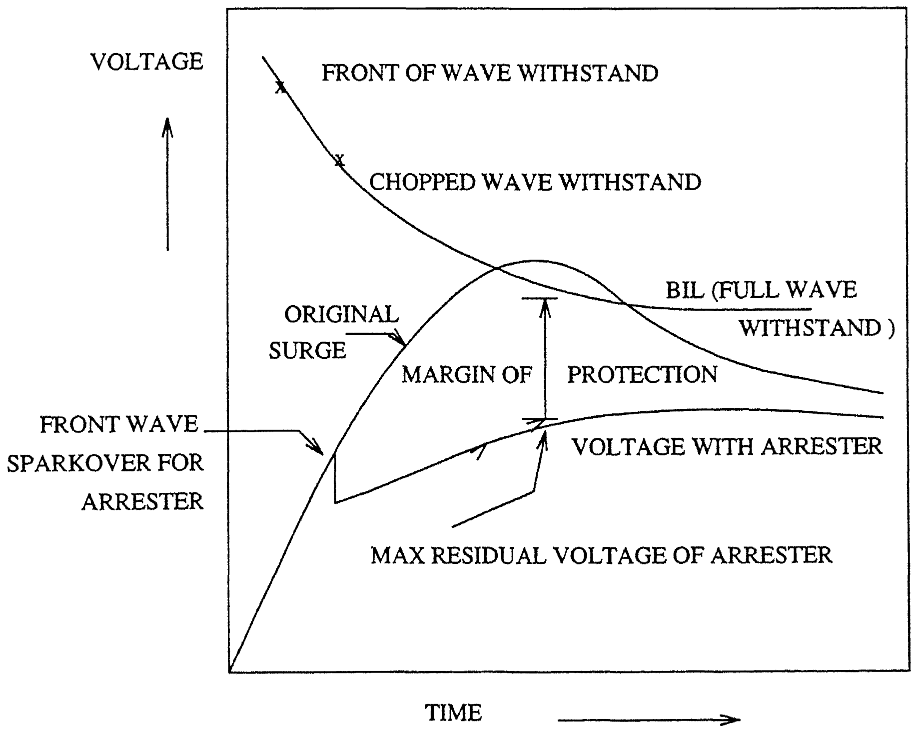


FIG 1.7 (a) PROTECTIVE MARGIN AND THE RESIDUAL VOLTAGE OF A SURGE ARRESTER

spark gap. The next generation were the gapped surge arrestors, with and without the current limiting blocks Finally , Metal oxide varistors (MOV) were introduced. These devices are briefly described below. Today's technology has resulted in MOVs with characteristics very close to that of a ideal protective device. Fig 1.7 (a) shows the protective margin of voltage and the residual voltage across a surge arrestor./25/

1.4.3.2 Spark Gaps

A Spark gap is formed between two electrodes placed in air at a certain distance. The shape of the electrodes may be spherical, cylindrical and so on. When a transient over voltage super imposed on the steady state voltage is applied across the spark gap, it initiates a spark whenever this voltage exceeds a predetermined level called the sparkover voltage. When the spark initiates, it develops into a arc with time. The transient voltage across the arc varies with time whereas the steady state voltage does not . When the transient over voltage magnitude reduces to an extent when the arc cannot sustain itself and it is interrupted as the transient over voltage travels away. Fig 1.8 (a) illustrates a typical voltage-time characteristics of a long air gap. /23/. The difference between the sparkover voltage and the steady state voltage is very large which severely limits the protection properties of the gap. Not withstanding the above limitation, spark gap still plays a major role in protection of transformer bushings and insulator strings. In the event of failure of the Surge arrestor, a spark gap on the bushing provide a second line of defense against insulation failure due to overvoltages and thus cannot be ignored.

1.4.3.3 Gapped Surge Arrestors

Gapped surge arrestors comprise an arrangement of spark gaps. They employ a string of metal plates held apart by insulating material. During operation, arcs are formed between any two contingent plates. Thus the arc is broken into a number of shorter arcs. This basic arrangement decreases the difference between the sparkover voltage and the voltage of the arc since the sparkover voltage depends on the distance between two contingent

plates whereas the voltage of the arc is across the entire arrangement.

The protection characteristics of the present day gapped surge arrestor have been improved by two basic innovations:-

(a) The arc voltage in an individual spark gap is increased by means of forming a chamber and increasing the length of arc by means of magnetic induction.

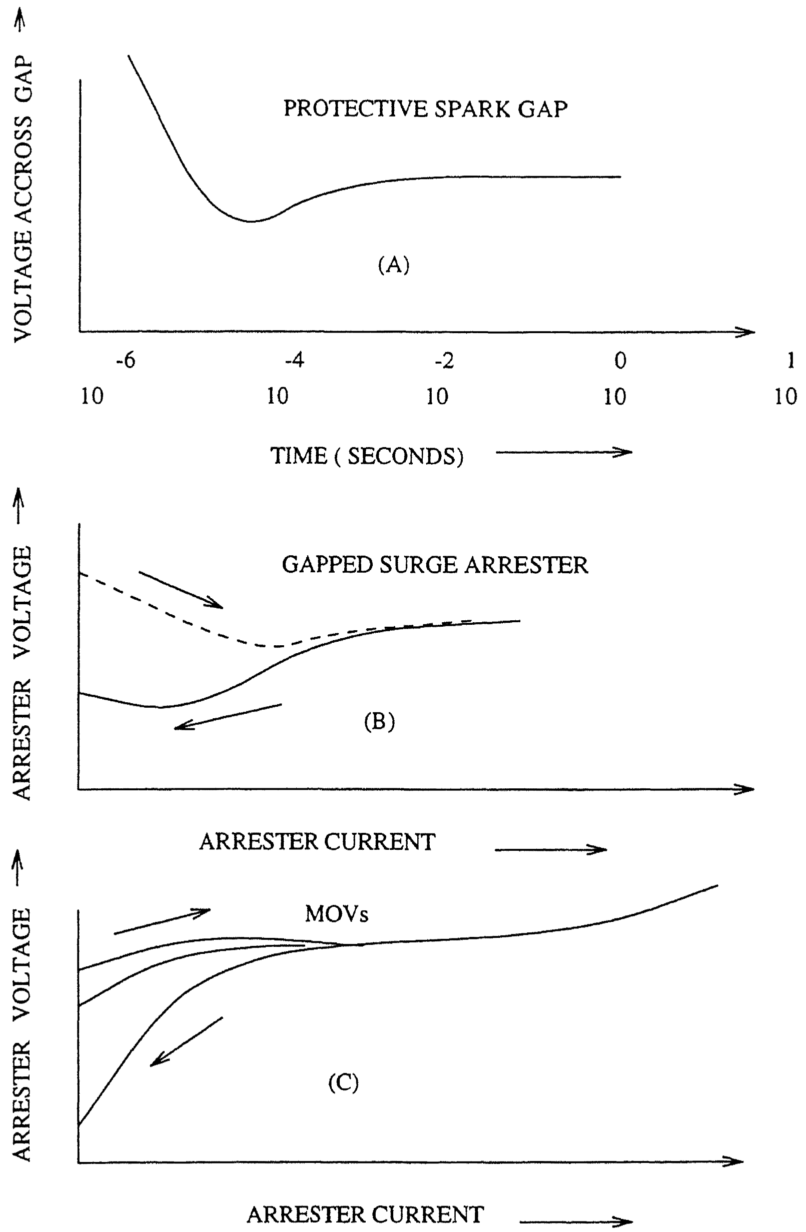


FIG 1.8 TYPICAL CHARACTERISTICS OF DIFFERENT TYPES OF OVERVOLTAGE PROTECTIVE DEVICES

(b) A current limiting block is connected in series with the spark gaps. This block is typically made of SiC, which has a non-linear current-voltage characteristics

A typical current-voltage characteristic is shown in Fig 1.8 (b). Note that the difference between the sparkover voltage and reset voltage is relatively low.

1.4.3.4 Gapless Surge Arrestors (MOVs)

It is manufactured of ZnO composite ceramic substances with nonlinear voltage-current characteristics close to the desirable (ideal) characteristics of a overvoltage protective device as described earlier. Fig 1.8 (c) shows one such typical characteristics. This is the reason that MOVs are rapidly becoming the preferred arrestor.

1.4.4 Effect of Pollution on Spark Gap Performance

The spark gap still plays a major role in protection of transformer bushings and insulator strings. In the event of failure of the Surge arrestors they provide a second line of defense against overvoltages and thus cannot be ignored. At the same time it is the device which is always exposed to the vagaries of nature which severely alters its performance. Effect of the change of atmospheric conditions etc cannot be ignored. Worst of all is the effect of pollution and subsequent corrosion of the electrodes. Unfortunately this area seems to have been not investigated adequately by researchers and need to be studied further in detail. Another purpose of this work was to investigate the effect of pollution and the subsequent corrosion of the electrodes on the performance of protective spark gaps in the laboratory.

The spark gaps are generally made of Galvanized Iron (GI). They are constantly exposed to elements of nature. Due to extensive industrialization and the consequent pollution caused by flue gases, chimney discharges, automobile emissions and dust, a thick corrosive layer is formed on the spark gap electrodes This is likely to alter the flashover characteristics of the spark gap Also gases like sulphur dioxide react with water vapors to form highly corrosive Sulphuric acid which gradually dissolves away the protective zinc coating on the iron . This exposes the base metal (Iron) to corrosion i e rusting. A thick layer of rust forms sort of an insulating layer which is integral to the spark gap electrodes. The properties of this layer leading to the deterioration of the surface finish of the electrodes alter the performance of the spark gap

It is likely that the sparkover voltage be exceeded excessively, thus defeating the very purpose of its installation.

Since atmospheric corrosion is a very complex and slow process improvisations were made to accelerate this process for the purpose of laboratory studies. Also attempt was made to artificially simulate the natural insulating layers by using materials like Kaolin and Resin coating. Effort was made to err on the safe side. Absence of literature in this field made the work little difficult.

CHAPTER 2

ELECTRIC FIELDS

2.1 Classification of Electric Fields

To understand the principle and functioning of the lightning conductor and the lightning discharge , it is necessary to understand the theory of electric fields. The total behaviour of insulating materials , is governed by the electric field configurations. Accordingly the electric field configuration can be classified into following types :-

(a) Uniform Field.

(b) Nonuniform Field

The classification is done on the basis of 'Schwaiger Factor' also called the Field Uniformity Factor, defined as :-

$$\eta = \frac{\hat{U}}{d \cdot E_{max}} = \frac{E_{avg}}{E_{max}}$$

For a uniform field η equals unity and it approaches zero for a extremely nonuniform field . In uniform field the electric field intensity throughout the gap in between the electrodes is uniform, which is very difficult to be achieved in practice. In non uniform fields the field in the space between the electrodes is not uniform due to nonuniform distribution of the voltage. Most of the field configurations existing in the global system are non uniform.

It is well established that where ever the field intensity becomes greater than the strength of the air, the air or the medium breaks down at these locations. This local breakdown of the medium is called ' Partial Discharge '(PD). The PD sets in only extremely nonuniform fields, whereas in

uniform fields there is no local breakdown , hence no PD. In nonuniform fields there is a sub classification taking into account the aspect of PD. The sub classification being :-

(i) Weakly nonuniform fields.

(ii) Extremely nonuniform fields.

As in case of uniform field, in weakly nonuniform fields it is seen that PD inception voltage is equal to the breakdown voltage hence no stable PD takes placein this configuration.

$$U_b = U_i$$

In extremely nonuniform fields, stable PD takes place before the breakdown, thus,

$$U_i < U_b$$

Schwaiger factor in this case is normally small, (less than 0.2). /12/ These types of fields are most common in power system. Table 2.1 gives a comparison of the types of fields described.

2.2 Theory of Breakdown of Air under Impulse Voltage

In order to understand the function of the lightning protective devices it is important to understand the theory of breakdown of Air under lightning impulse voltage. The next few paragraphs briefly describe the same. It would be pertinent to revise the theory of development of discharges leading to final breakdown of the dielectric medium. One question arise as to the polarity of the applied voltage. It has been verified by a number of researchers that bulk of the lightning discharges in nature is of negative polarity . Only a few percent is of positive polarity. Hence it would be prudent to perform the investigations using negative polarity impulse voltage. However since the last stage of the lightning strike is of negative leader and the return stroke of positive leader we will study the breakdown phenomenon of both polarity briefly.

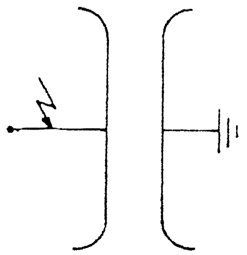
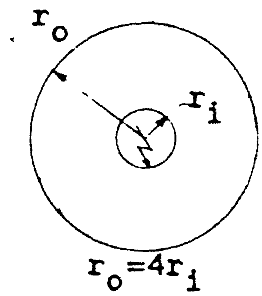
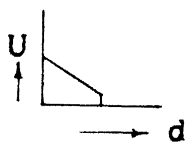
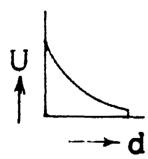
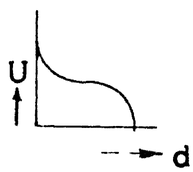
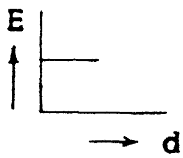
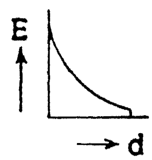
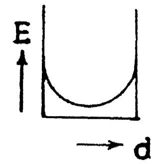
FIELD CONFIGURATION	UNIFORM	WEAKLY NONUNIFORM	EXTREMELY NONUNIFORM
Electrode Configuration			
Potential Distribution			
Field Intensity			
U_i vs U_b	$U_i = U_b$	$U_i = U_b$	$U_i < U_b$
η	≈ 1.0	$0.2 < \eta < 1.0$	$\eta < 0.2$

FIG 2.1 COMPARISION OF THE TYPES OF ELECTRIC FIELDS

2.2.1 Breakdown Voltage Characteristics in Extremely Nonuniform Fields

The quasi continuous partial discharge (PD) process in air is basically characterized by three distinguished stages of its development. These

essential stages are avalanche, streamer and leader discharges. It took a very long time (over two centuries) for researchers to distinctly separate and understand these partial discharges. Thanks to the advance electrical measurement and photographic techniques.

For a stable PD process to be able to establish a fairly good conductive path between the electrodes, it requires to extend itself sufficiently in the gap. When this is accomplished, the discharge process is rendered 'instable', leading to 'spark breakdown' of the dielectric between the two electrodes. Before the breakdown , depending on the electrode configuration and gap distance, three main types of stable PD may take place. The possibilities are :-

I. A stable avalanche or glow discharge, leading to spark over by forming an instable leader towards its advance stage, and finally the arc.

II. An avalanche discharge continued with stable streamer or bunch discharge, followed by a spark breakdown producing an instable leader in the last stage, and ultimately an arc.

III A dense filamentary streamer corona is followed by stembunch discharge. Stable leader channels are then formed , accomplishing the spark breakdown with an arc.

The breakdown voltage characteristics are distinguished accordingly. Fig 2.2 shows a schematic of possibilities of accomplishing spark breakdown through these mechanism for different types of voltages. For greater details on the types of PD and the theory of their formation one may refer to 'High Voltage Insulation Engineering ' by Ravindra Arora / 12 /.

It must be made clear that in all cases, it is the 'instable leader' which ultimately gives rise to the required conductivity of the breakdown channel, developing finally into an arc. Thus it is only the leader discharge which can acquires the sufficient conductivity to begin the plasma

state of the gas converting into an arc towards its final jump. Among many parameters, the magnitude of the breakdown voltage depends strongly upon the type of *stable* discharge that precede the spark breakdown

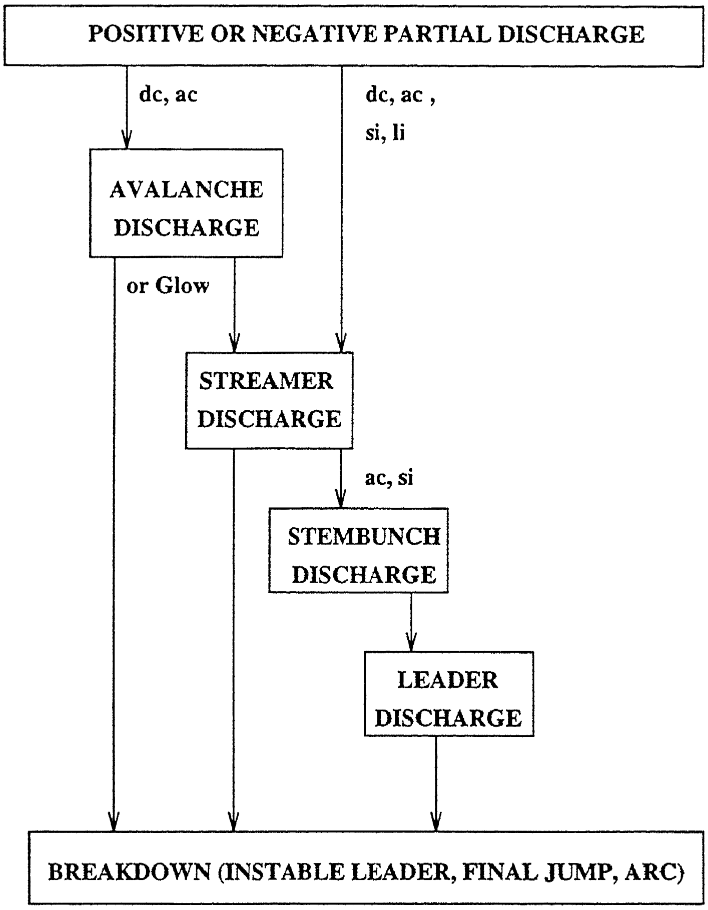


FIG 2.2 SCHEMATIC OF BREAKDOWN INITIATED BY DIFFERENT TYPES OF VOLTAGES

There is significant effect of the type and polarity of the applied voltage on the breakdown strength of a dielectric. In case of impulse voltage (lightning 'li' , switching 'si' impulses) not only the polarity

but also the time required to reach the crest of the voltage 'T_{cr}' affects the breakdown voltage. As a matter of rule higher voltage of negative polarity is needed to achieve breakdown as compared to positive polarity in extremely nonuniform field / 12 /. Beginning with the lightning impulse , lower breakdown voltages are achieved as the T_{cr} is increased. Depending on the electrode configuration and the gap length, a minimum of breakdown voltage is measured for a particular T_{cr} of the applied voltage. On increasing the T_{cr} further , higher breakdown voltages are measured again.

Breakdown with stable Avalanche discharge and stable steamer discharge may take place for very small gaps ie. up to 2 cm and one meters respectively . For longer gaps the breakdown take place with both, stable steamer and leader discharge./ 12/.

2.2.'2 The phenomenon of Statistical Time Lag

On applying an impulse voltage of sufficient magnitude to cause breakdown in the gap, the actual spark breakdown takes place after a time delay known as 'time lag'. The time lag primarily depends upon the shape and magnitude of the applied voltage and the electrode configurations. As for initiation of a breakdown, presence of electrons is essential in order to begin the avalanche process. With dc or with slow changing ac voltages, the number of initiatory electrons produced by cosmic rays and natural UV light are sufficient to initiate a breakdown. However with impulse voltages , especially with pulses of very short duration like li , it is possible that breakdown may not occur even if sufficiently high voltage is applied due to absence of initiatory electrons at that instant. This may also be called as '*Stastical time lag*' t_s . T_s depends on degree of preionisation in the gap, which in turn depends on the area of the electrodes, the gap distance and the magnitude of the radiation producing the primary electrons. T_s may be reduced by artificially irradiating the electrodes or by applying higher voltages.

There is certain finite time needed for the propagation of the leader

to reach the other electrode . This is known as the '*propagation time t_p*' .Total t_p depends on the individual types of PD and their extent in the gap just before breakdown. The total time taken needed to breakdown (T_b) is the sum total of the time lag (T_s) and the propagation time (T_p), ie.

$$T_b = T_p + T_s$$

The times T_b, T_s and T_p represent the statistical time lag. They have been shown in Fig 2.3 (a). Because of the statistical nature of the time lag T_s , out of a given number of impulses of a magnitude higher than the minimum (U_s) applied to a gap only a certain percentage accomplish breakdown. The probability of breakdown for a given impulse voltage is determined experimentally. The ratio of the number of breakdown to the total number of impulses applied gives the probability The distribution function of the breakdown probability is shown in Fig 2.3(b). $U_{b\text{-}100}$ represent the 100 % breakdown voltage also known as the 'protective level' voltage. $U_{b\text{-}50}$ is the 50 % breakdown voltage, that is , only half the number of applied impulses will cause breakdown. $U_{b\text{-}0}$ is called the 'impulse withstand level' voltage where none of the impulse applied will cause a breakdown.

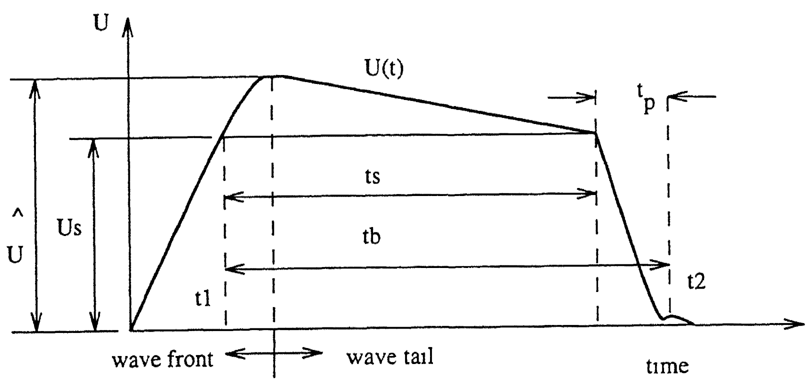


FIG 2.3(a) STASTISTICAL TIME LAG

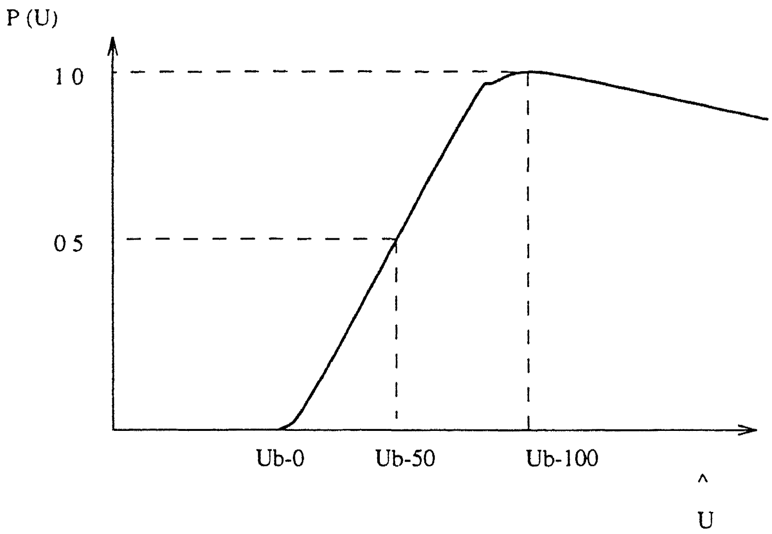


FIG 2.3(b) PROBABILITY OF BREAKDOWN WITH IMPULSE VOLTAGE

CHAPTER 3

NATURE OF LIGHTNING

3.1 Lightning Phenomena

Physical manifestation of lightning have been noted in ancient times but the understanding of the lightning is relatively recent. Franklin carried out experiments on lightning in 1744-1750 but more knowledge has been obtained in last 50 years. Study of lightning gained importance when electric transmission lines and other installations had to be protected against the Lightning strokes.

The phenomenon of lightning is generally regarded to be natures means of keeping ' Global Electric System ' balanced. A widely accepted view of the global electric system is that the earth and the lower ionosphere are two highly conductive surfaces separated by an imperfect insulating atmosphere , that is to say , a large condenser with some leakage . The lower ionosphere (height of range 50 - 75 kms) and the earth surfaces are highly conductive. This is due to the existence of ambient plasma state of the atmosphere in this layer. One of the major cause for this state is the phenomenon of Auroras. Auroras are lights emitted when atoms in the ionosphere are stuck by high-energy electrons coming from the sun in the form of solar wind./26/

It is now known, though though not fully understood, that auroras occur due to some complex interaction between the solar wind (a thin plasma of hydrogen ions and electrons constantly streaming away from the sun) and the earth's magnetosphere. The matter in the earth's magnetosphere is in the form of plasma consisting of charged particles. Some of the solar wind particles interact with these particles in the magnetosphere to cause the electrical discharges that produce the auroral displays. Thus, the magnetosphere behaves as a gigantic generator of that produces up to ten million megawatts of electrical power. The electric currents generated in the magnetosphere are guided along the lines of earth's magnetic fields. These field aligned currents are responsible for the curtain shape of the

auroras. They also control the location of the auroras. The field aligned currents, by complicated processes, reach the lower ionosphere forming the lower edge of the auroras at a height of about 100 kms.

Over fair weather areas there is a downward transfer of the positive charge , which tends to reduce positive potential of ionosphere as well as neutralize the negative charge on the earth. Within global system, lightning discharge transfers positive charge upward at a rate sufficient to sustain a balanced dynamic system ; that is, , the regular current flow between the positively charged ionosphere and negatively charged earth is controlled by and maintained by global thunderstorm activity.This can be schematically seen in Fig 3.1. Wahlin /27/

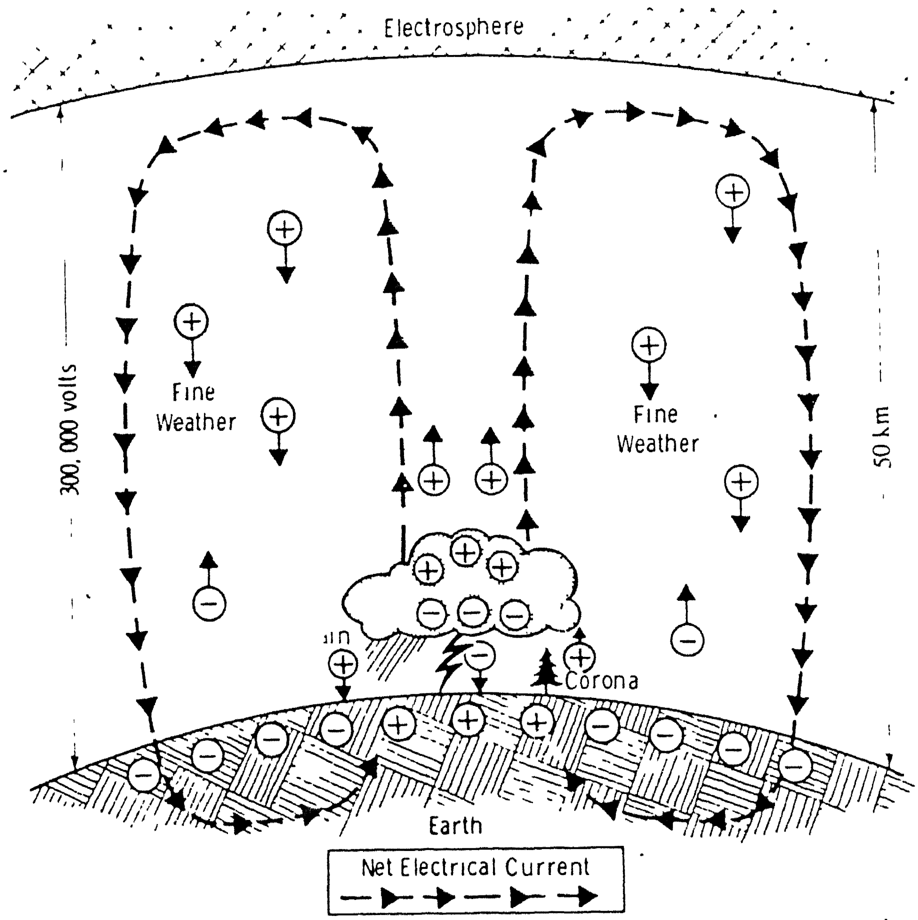


FIG 3.1 Illustration showing a thunderstorm acting as a battery to keep the Earth charged negatively and the atmosphere charged positively. Atmospheric electrical currents flow downward in fine weather and upward in thunderstorms. Thunderstorms deliver charge to the earth by lightning, rain, and corona discharges. Adapted from Uman (1971)

It is estimated that over the earth's surface as many as 2000 thunderstorms discharges , by lightning, are continually in existence.

Active thunderstorms discharge, by lightning, at the average rate of 20 Coulombs every 10 seconds , which is equivalent to approximately 2 A of steady current. The capacitor formed by lower ionosphere and earth surface is more or less at a steady potential of 300 kV , earth being negative and ionosphere being positive. As the average air - earth current is of the order of 1500 A , this would indicate the existence of about 2000 active thunderstorms, and even more if minor storms are taken into consideration between ionosphere and earth. The current density at the earth's surface is estimated at 3 X 10^{-12} A/m^2. These figures are average values and have been arrived at using measurements of air conductivity and potential gradients . The steady electric field at the earth's surface is about 3 V/cm in fair weather conditions and during thunderstorms development this can rise to 500 to 600 V/cm beneath the thunderclouds and to much higher values near ground level below a stepped leader at the time of lightning strike. / 1,2 ,7-9 /. In view of the above, it must be appreciated that a lightning discharge must transfer to earth negative charges . Thus the lower end of the cloud will be negatively charged, which induces a positive charge on the ground.

During thunderstorms, positive and negative charges become separated by inter play of air currents, ice crystals in upper part of the cloud , and rain in the lower part. Electrically the thundercloud may be regarded as a charge separation device or electric generator satisfying the needs of " global system". This process is subjected to many theories , revealing a few observable facts of interest; clouds are charged negatively with a layer of positive charge at the top , which is typically present up to 9-12 kms above the ground surface, the cloud base may be as low as 150 m.

The Lightning stroke is established by a 'Stepped Leader ' which incepts in the cloud region when the local charge concentration increases the potential gradient to acquire the critical breakdown value for air. In dry weather conditions the potential gradient required for the breakdown of air is high, but in humid conditions , it reduces considerably. The leader propagates rapidly in steps of about 50 m in an highly ionized space with a velocity of about 10 cm/μs , in the process charge is brought down at the rate of 600 to 2,600 A /27/. As the leader head approaches the ground ,

positive charge induced in the target area intensifies. However point of strike remains undetermined until leader descends to a suitable striking distance to the surface . It is well known that the field configuration determined by the earth object determines the breakdown strength at this instant. The strike point on the earth depends upon the potential gradient below the leader channel and distribution of the space charge in the atmosphere. This implies that not only high objects and elevations are prone to receive the stroke but also the plains and even objects in the valleys between the mountains. At this stage , a short positive streamer rises from the earth called the ' *return stroke*' . It is regarded as an intense positive current discharge which develops because of high induced field at the particular location. The return stroke appears as a intense luminous discharge which we see as a 'flash' or the 'instable leader' . After the first return stroke it is usual for another region to provide sufficient charge for a second stroke or several more , separated by intervals of 10 to 20 msecs. This return discharge of one stroke or succession of strokes is called flash . The current in a li stroke is varying, under exceptionally intense storm conditions it can exceed to even 100 kA. Average charge released per flash is about 25 Coulombs.

3.2 Lightning Stroke Characteristics

Extensive work has been carried out to obtain the Lightning strokes characteristics since 60's and early 70's /1,2, 7-9/. Uman compiled in details the quantitative aspect of usual negative cloud to positive earth Lightning strokes. One of the bottlenecks while working on Lightning was the non availability of the impulse generators and the measuring equipment. Band widths of the measuring equipment available were not sufficient to analyze the characteristics of the Lightning currents.

Detailed investigations were carried out at the "Pessenberg Tower " in south Bavaria /10/ in which current wave forms were of actual Lightning were recorded and spectral analysis was carried out .

The standard Lightning voltage impulse is defined as 1.2/50 μs by IEC 99 -1. It also laid down the standard tolerances as $\mp$ 20 % on the front time and $\mp$ 30 % on the time to half value./ 11 /

The energy in a typical Lightning is calculated considering the value of 10^8 V to 10^9 V for the breakdown voltage for the gap distance between the cloud and the ground and assume a total discharge of 20 C. The energy released is in the order of 10^{13} , in the one or more strokes that constitutes the total discharge. The crest current per stroke, which may rise in 1 or 2 μs and fall to half its value in 40 t0 50 μs , is about 20 kA on an average, but it can reach several times this value depending upon the atmospheric and geographical conditions. The energy dissipated in the electrical discharge channel is expended in several processes. Small amount of energy produce dissociation of molecules , ionization , excitation of the earth's magnetic field. About 1% is spent in the kinetic energy of the channel particles , and 0.4 % in radiation. A large portion of the energy, about 98 % is consumed in the sudden expansion of air due to the heated arc channel. Some fraction of the total energy causes heat or ignites fire, at times, or in fracture of the earth or the grounded object that it strikes. In general Lightning returns to the global system the heat energy that originally created the charged clouds.

3.2.1 Breakdown Strength of Air with Lightning Impulse

Breakdown strength of air is a complicated phenomenon which not only depends upon its atmospheric conditions but also upon the field configuration determined by shape and size of the electrode and the gap distance . This has been discussed in detail in Chapter 2.

The phenomenon of breakdown with Lightning impulse is different because of short rise time of the impulse as well as its small duration, no stable PD are able to take place in this case. In this case breakdown is directly accomplished by an instable leader followed by an arc. In case of Lightning, the breakdown also depends upon statistical time lag which is a function of the voltage applied and availability of the initiatory electrons. The breakdown strength not only depends upon the irradiated condition of the electrode but also upon the extent of pre-ionisation available in the gas / 12 /. This is the reason power system installations attract Lightning the most.

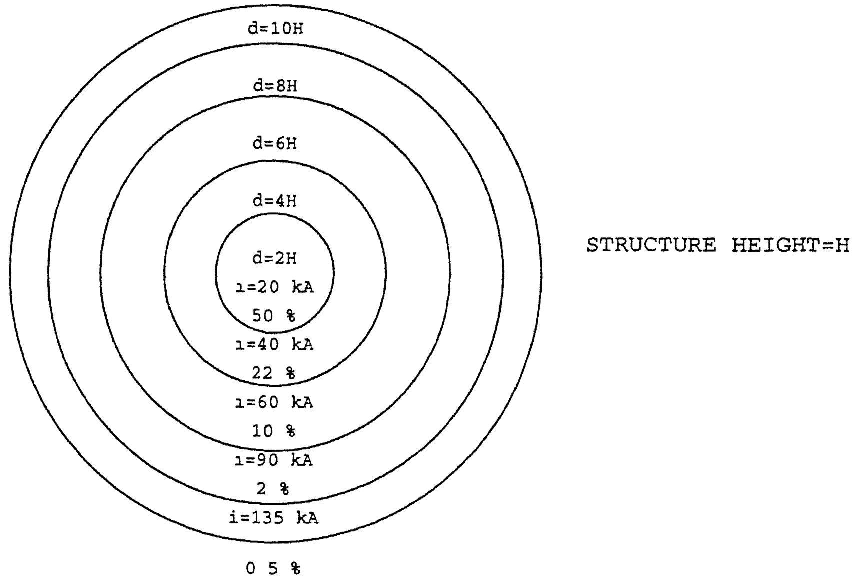
3.3 Probability of Lightning Stroke Striking the Ground

As would be expected, the frequency of Lightning strokes is proportional to the number of thunderstorm days in a particular area on the earth. A model to determine the ' attractive area ' of a conducting structure is given by Golde / 6 /. The same has been adopted by BSI code of practice and it forms the basis to determine the zone of Protection in the IS Code 2309:1989. Golde developed formulas for estimating the the frequency of Lightning strokes per thunderstorm days (average number of thunderstorms in a year), taking into account the location from the equator. Thus occurrence of Lightning strokes in a particular area can be calculated giving the significance of Lightning protection and assessment of the need of Lightning protection. The thunderstorm days also called Isokeraunic level of all the countries is maintained at The World Meteorological Organization in Geneva. IS 2309:1989 specifies this level throughout the country.

It has been stated that the attractive area (also called the 'striking Radius') of a Lightning conductor increases with increasing severity of the discharge, and that a vertical conductor of height 'H' attracts to itself Lightning strokes of average intensity (20 kA,which corresponds to 50 % of Lightning strokes) over a circular area of radius 2H around its base, refer figure 3.2, called the attractive area. Thus the zone of protection of a Lightning conductor may be described as an statistical quantity because of the uncertainty of the severity of the stroke.

3.3.1 Shielding of the Power System against Lightning

The established method of providing a Lightning discharge protection on power transmission lines is the overhead "ground " conductor. One or more of these are installed so as to provide protective angles of 45, 30, and 12 degrees for tower heights of 50, 100, and 150 ft, respectively. Considerable amount of work has been done about shielding failures / 3 / verses the protective angle. Shielding has increased importance for the high voltage lines . According to Golde flashover on 275 kV lines are mainly due to the shielding failures. For the practical purpose of providing an acceptable degree of protection of an ordinary structure , a protective angle of 45



(a)

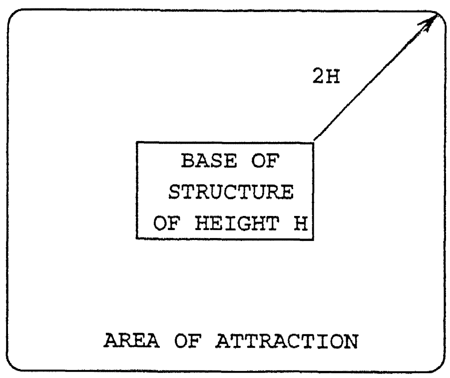


FIGURE 3.2. ATTRACTIVE AREA OF CONDUCTIVE STRUCTURES
(a) Variation of attractive distance with magnitude of lightning current and frequency of its occurrence.

(b) Average area of attraction.

degree is adopted for a single conductor either vertically or horizontally arranged, refer figure 3.2.

3.3.2 Importance of the Return Stroke

Among numerous other factors ,the probability of Lightning stroke striking the ground or an object on the ground depends on the extension or the reach of the last stage of the discharge, having originated from the clouds. Only under the circumstances when the gap distance between the the object and extension of the discharge is minimized to a certain level, the Lightning is able to strike the object. This gap distance is called as the 'striking radius' or 'attractive distance' (r_s). Another important condition for the Lightning to be able to strike on an object is that the length of the so called last stretch should be equal to or smaller than the "length of the return stroke step", (l_s), of the original discharge as shown in Figure 1.4 (a) and discussed in Chapter 1. The tip of the downward leader propagates towards the ground, simultaneously because of the the electric field at the sharp objects or irregularities on the ground exceeding the breakdown strength of air , *one or more* upward discharges are initiated upward from these points. When one of the upward discharges joins the downward leader, the latter is connected to the ground potential /14/ . This is called the attachment process which has been described in detail in the following section.

3.3.3 The Attachment Process

In order to understand the phenomenon of the lightning strike to a target it would be necessary to study the various phases of the Attachment process. From the ground based measurements of the electric field near the ground, the distribution of charges in a stormy cumulo-nimbus cloud can be modeled essentially by two charges, the upper positive and the lower negative. See Fig 3.3. More accurate models include an additional positive charge lower than the negative. This results into induced positive charge on the ground in the region below the negatively charged cloud. These models indicate electric field intensity as high as 50 kV/m above a flat conducting ground /16/ four to five times than actually measured over land. This is because of corona discharges initiated from surface irregularities as soon as local field exceeds a critical value. Positive space charge thus

generated reduces the electric field near ground being of the same polarity./28/

The first of the four phases of the development of a li stroke corresponds to the initiation of the lightning stroke by the formation of a leader within the storm cloud that advances in steps in the downward direction. Simultaneously corona discharge at the sharp points on the ground begins to grow. Depending on the local conditions, an upward leader may be generated, particularly at the tip of the lightning rod (this distance is called the initiation distance, Phase 2). By propagating upwards, the positive leader , also known as return stroke, shortens the gap distance to be bridged thus influencing the downward leader to alter its trajectory (this distance is called the attraction distance , Phase 3) . The two leaders finally meet (phase 4) . The striking distance D is the distance between the junction zone and the lightning conductor point.

Since upward leaders may be originated from many electrodes on the ground in the immediate vicinity of the downward leader, the most appropriate upward leader in the sense of its location, strength and instant of initiation forms the 'return stroke' to meet the downward leader determining the lightning impact point. In other words , it can be said that, *a rod capable of initiating an upward leader earlier will form a preferential impact point for the lightning.*

Since the velocity of the propagation of leader discharge is known and will be generally same for all the upward leaders, one that is initiated earliest, determines the shortest gap distance and has the most vigorous corona discharge will most likely to meet the downward leader. Since statistical time lag t_s is an indicative of the delay in initiation of the leader, it is a very important parameter while comparing different types of lightning rods. Lower t_s should indicate a more preferential target point.

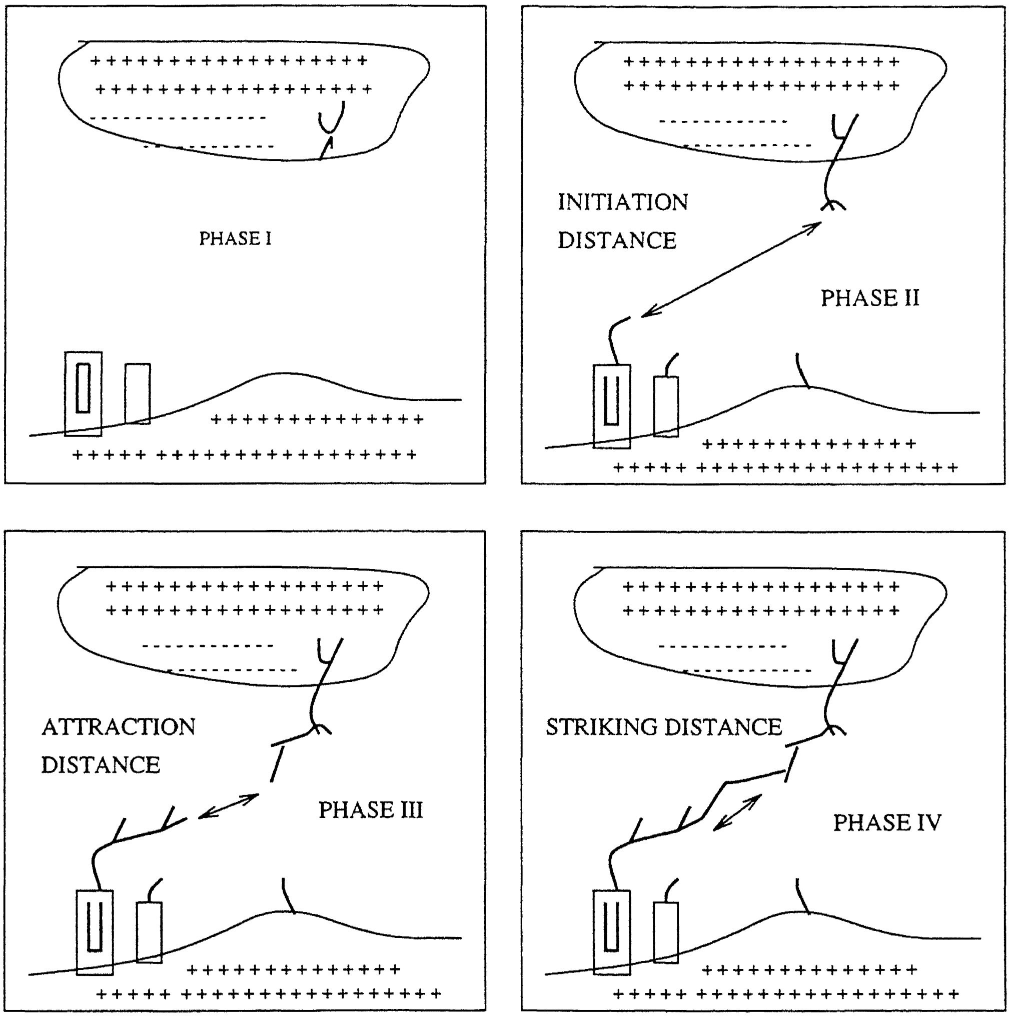


FIG 3.3 PHASES OF ATTACHMENT PROCESS IN A LIGHTNING STROKE

CHAPTER 4

THE EXPERIMENTAL SET-UP

The experimental setup along with fixtures fabricated for the investigations is described in this chapter. Since the investigations were performed at both the HV Lab IIT Kanpur and at UHV Research lab at CPRI, Hyderabad it would be pertinent to mention the sequence of investigations to help in understanding the experimental setup .

4.1 Sequence of Experimental Work Performed

The investigations were performed in the following sequence:-

(a) Investigation for the suitable shape of the Lightning conductor Air Terminal for longer gap lengths (meters) at UHV Research Lab at CPRI Hyderabad.

(b) Reinvestigation of the results found at UHV Research Lab, CPRI Hyderabad at HV Lab, IIT Kanpur for small gaps (cm).

(c) Investigations of Protective Spark Gaps in clean, polluted and corroded conditions at HV Lab , IIT Kanpur.

4.2 Set-up for the Investigation of the Shape of Air Terminal

As already mentioned above , these investigations were performed at both the labs but for different gap ranges. Hence two entirely different set-ups were needed at each place. Only negative polarity impulse of standard wave shape, 1.2/50 μs was used for the reason already mentioned earlier. The necessary factors kept in mind while preparing the set-up were:-

(a) The electric field configuration between the electrodes was extremely non-uniform as is in nature in order to correctly simulate the lightning strike conditions.

(b) A plane point configuration was selected with the plane simulating the cloud with a negative impulse voltage impressed on it and the point being grounded and depicting the lightning rod.

(c) Provision was made to change the tip of the Air Terminal (grounded electrode).

(d) It was made possible to fix a number of lightning rods (grounded electrodes) simultaneously to be able to physically compare the relative attractive effect of each of them Care was taken to space them in such a way that they do not affect the field at the other electrode considerably.

(e) The cloud electrode was suitably shaped to avoid any sharp points to suppress corona discharges which may distort the electric field and thus the measurements.

Thus keeping the above considerations in mind, the experimental set-up at both the labs essentially consisted of the following parts:-

(a) A suitably sized circular bowl shaped cloud electrode which was duly suspended in air by insulating supports. The HV impulse was impressed on this electrode. There was a provision to vary its height in order to get different air gap distances.

(b) A metal base plate in square shape which was grounded to depict the ground. There was a provision to mount the lightning rods on this ground plate having different shapes of air terminals either singly or in multiple configuration. This plate was raised above the floor to avoid the affect surrounding structures on the field.

4.2.1 Set-up for the Investigation of Shape of Air Terminal at UHV Research Lab, CPRI Hyderabad

The set-up is shown in Fig 4.1 and photo. 1 . The cloud electrode was made of a 4 meter diameter circular toroid ring with a fine aluminum wire mesh stretched below it to make a hollow shaped bowl. This was suspended from the Mock up towers using polypropylene (PP) ropes. It was duly braced from all the four sides to maintain a horizontal level position in spite of the wind which tended to sway it sideways. The ropes could be individually adjusted to shift the electrode to any desired height and position.

The ground plate was made of 10 mm thick 2 m square steel plate. This plate was supported on four insulating pedestals at a height of 1.18 meters above the ground. This plate was grounded using a copper strip. There were

four six inches long pipes (3/4" dia) welded on it to provide fixtures for the lightning rods at positions shown in Fig 4.2 (a). The air terminals were mounted on a 1.20 meter long GI pipe which in turn was fixed to the small pipes welded on the base plate making a bayonet joint (see fig 4.2 (b)).

The impulse generator was connected to the cloud electrode . Details of the Impulse generator are given in the next paragraph.

4.2.1.1 The Impulse Generator at UHV Research lab of CPRI at Hyderabad.

A Marx type 25 stage, outdoor impulse generator of Haefly, Switzerland was used to produce the required HV impulse of negative polarity. Due to the extended length of the lead wire from the impulse generator to the test bay (approx 60 meters) and the size of the cloud electrode the wave shape of 1.2/50 μs could not be achieved. The front time typically varied between 2 to 3 μs and the tail time between 45 to 55 μs. The measurements were recorded using the computer based control and data recording system supplied with the impulse generator by Haefly. The important specifications of the impulse generator are given in table below:-

SER NO	SPECIFICATION	VALUE
1.	MAX CHARGING VOLTAGE	5 MV
2.	MAX STORED ENERGY	500 kJ
3.	NO. OF STAGES	25
4.	VOLTAGE/STAGE	200 kV
5.	HEIGHT	18 m
6.	RC DIVIDER RATIO	3579:130
7.	DIVIDER CAPACITANCE	600 pF
8.	DIVIDER RESISTANCE	40 OHMS

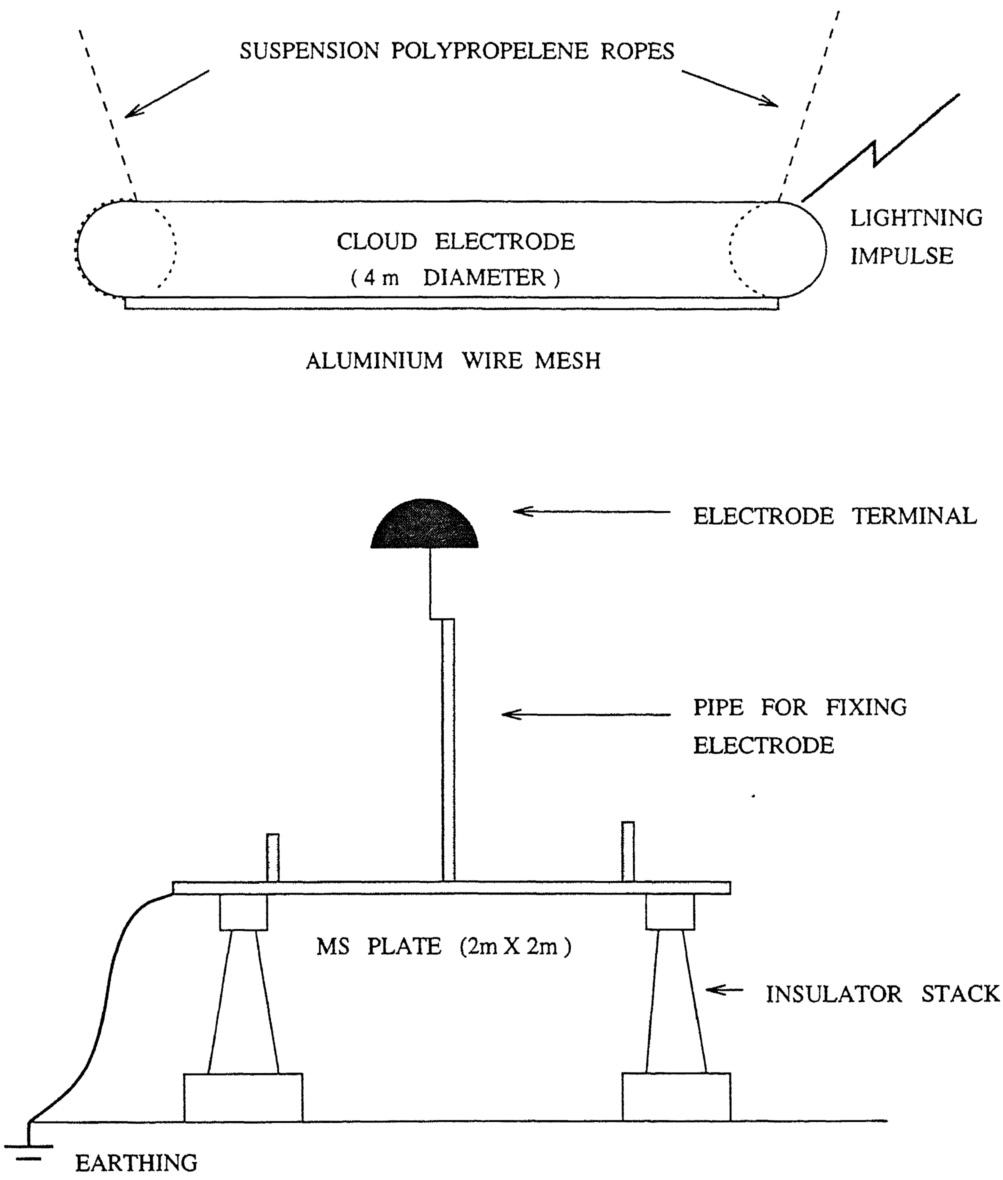


FIG 4.1 : EXPERIMENTAL SETUP FOR INVESTIGATIONS UNDER LONG GAPS

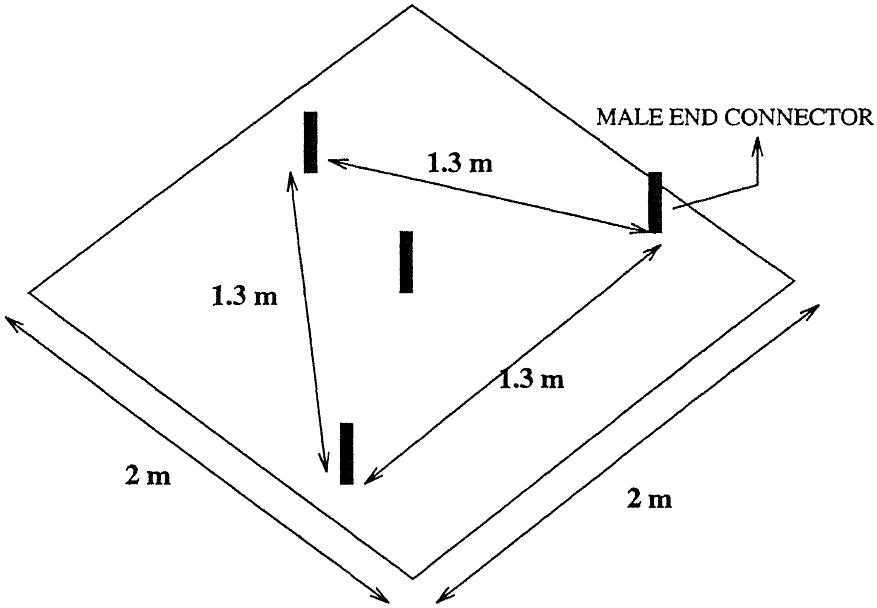


FIG 4.2 (a) VIEW OF THE GROUND PLATE WITH MALE END CONNECTORS

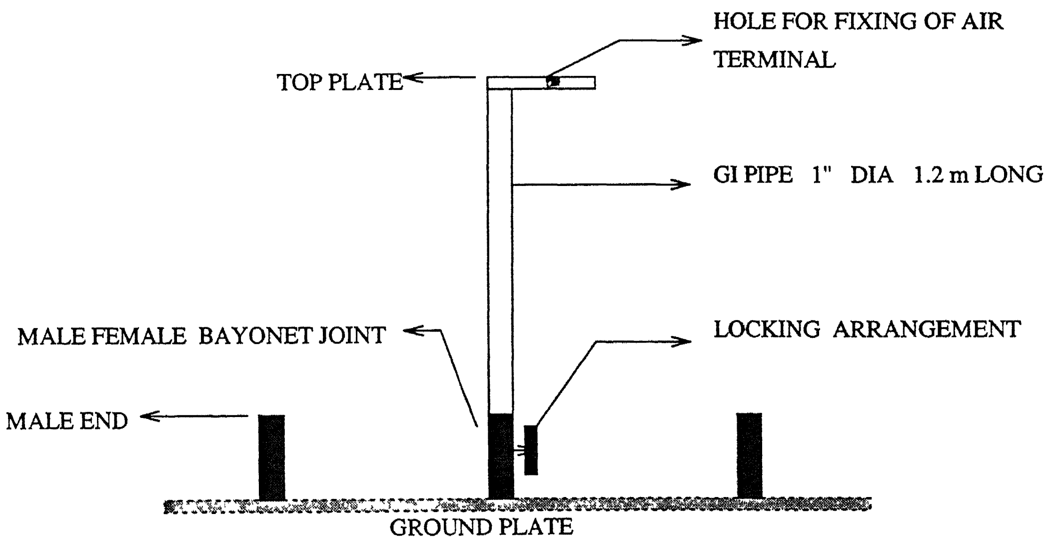
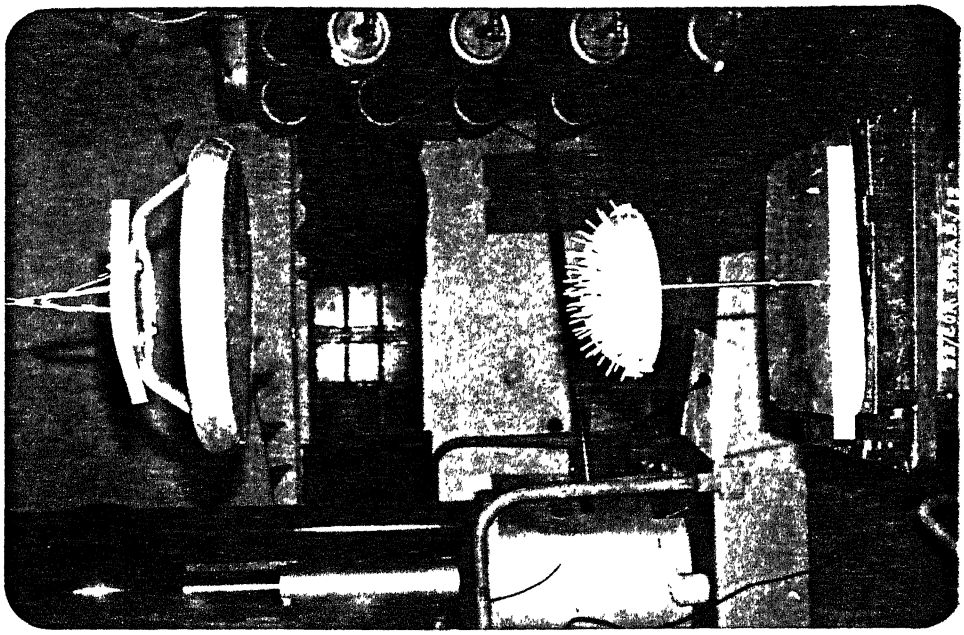


FIG 4.2 (b) FIXTURE FOR FIXING OF THE AIR TERMINALS ON THE GROUND PLATE

IOTOGRAPH 1 : EXPERIMENTAL SET UP AT CPRI, HYDERABAD



PHOTOGRAPH 2 : EXPERIMENTAL SET UP AT IIT KANPUR

4.2.2 Set-up for Investigation of Shape of Air Terminal at HV Lab, IIT KANPUR

The set-up is shown in Fig 4.3 and photo. 2 . The cloud electrode was made of a 40 cm diameter toroid ring with a 22 gauge aluminum sheet stretched below it again to make a hollow shaped bowl. This was suspended from the ceiling using toughened glass insulator string The suspension could be adjusted to shift the electrode to any desired height and position.

SPECIFICATION OF IMPULSE GENERATOR AT IIT KANPUR

SER NO	SPECIFICATION	VALUE
1.	MAX CHARGING VOLTAGE	500 kV
2.	MAX STORED ENERGY	4.4 kJ
3.	NO. OF STAGES	4
4.	VOLTAGE/STAGE	125 kV
5.	INPUT VOLTAGE	440 V, 3Φ
6.	CAP DIVIDER RATIO	750:1
7.	DIVIDER CAPACITANCE	1.5 nF
8.	WAVE SHAPE OF LI	1.2/50 μs

The ground plate was made of 2 mm thick square aluminum plate having sides of 30 cm. This plate was supported on four insulating pedestals at a suitable height above ground. The plate was grounded using a copper strip. There were a number of holes drilled in it at appropriate locations to be able to fix the air terminal electrodes. The impulse generator was connected to the cloud electrode . Details of the Impulse generator are given in the next paragraph.

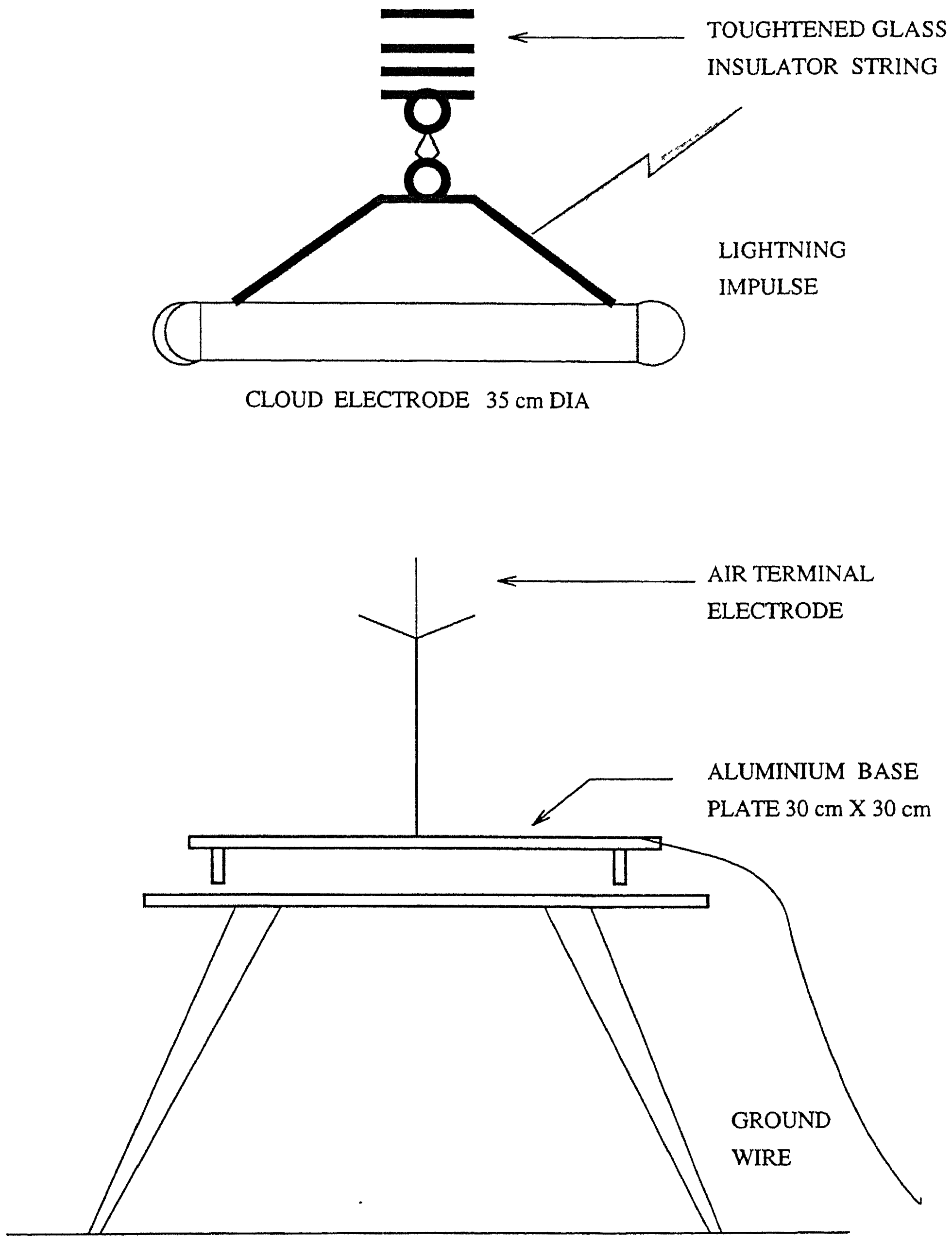
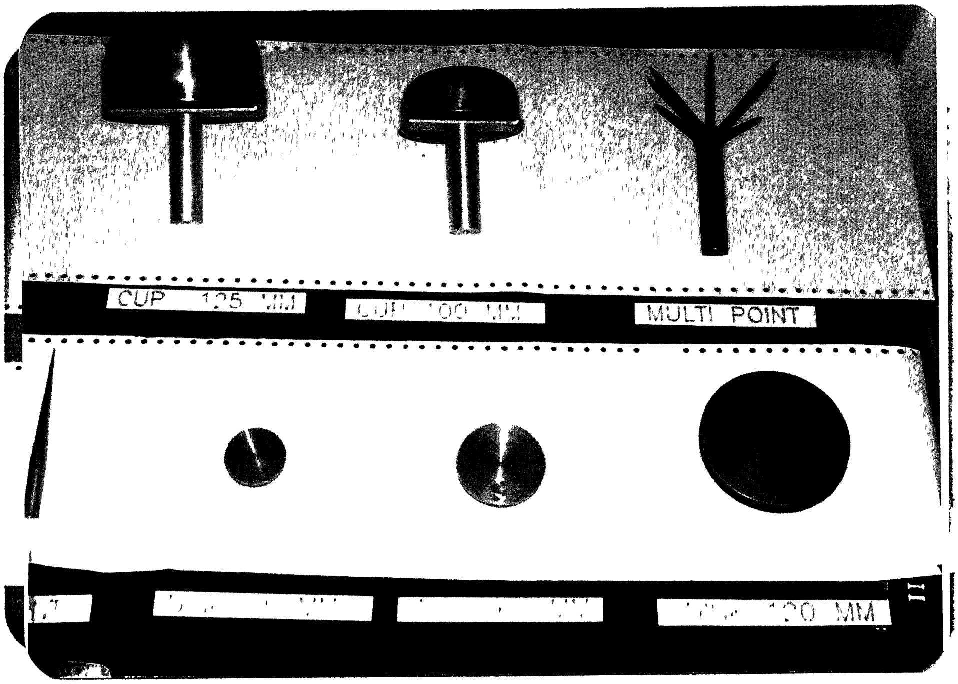
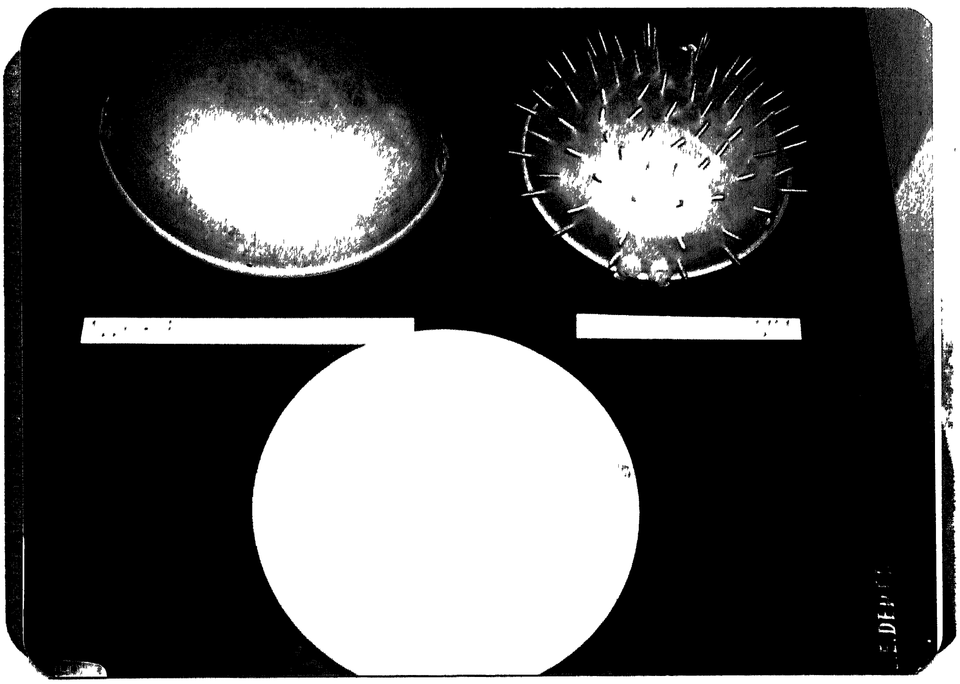


FIG 4.3 : EXPERIMENTAL SETUP FOR INVESTIGATIONS UNDER SMALL GAPS





PHOTOGRAPH 3 AND 4 : TEST AIR TERMINAL ELECTRODES USED

4.2.2.1 The Impulse Generator at HV Lab IIT Kanpur

A Marx type 4 stage, indoor impulse generator of Tür Germany was used to produce the required HV impulse of negative polarity. The measurements were recorded using a capacitive voltage divider of ratio 750:1 and passive probe of 10:1 to a 8-bit digital storage oscilloscope of KIKUSUI make, Model No COR 502U . It is a 100 MSPS (mega samples per sec) oscilloscope and has sufficient resolution for the purpose of our investigations. It was also interfaced with a PC-XT and the data was transferred to it through the serial port. A Plotter was directly connected to the oscilloscope to obtain hard copy of the data recorded. Specifications of the impulse generator are given in table given above.

4.2.3 Test Electrodes used as Air Terminals

A number of test electrodes were fabricated to perform experiments with various shapes of the air terminal to study relative attraction for lightning strikes and the probability of lightning strike on them . They are shown in photographs. 3 and 4 and listed below:-

(a) Point
(b) Multi Point
(c) Rod
(d) Disc 25 mm dia
(e) Disc 45 mm dia
(f) Disc 65 mm dia
(g) Disc 100 mm dia
(h) Disc 255 mm dia
(j) Smooth Inverted Bowl 250 mm dia
(k) Inverted cup 125 mm dia
(l) Spiked inverted bowl 250 mm effective dia

They were fabricated using brass, aluminum and steel materials.

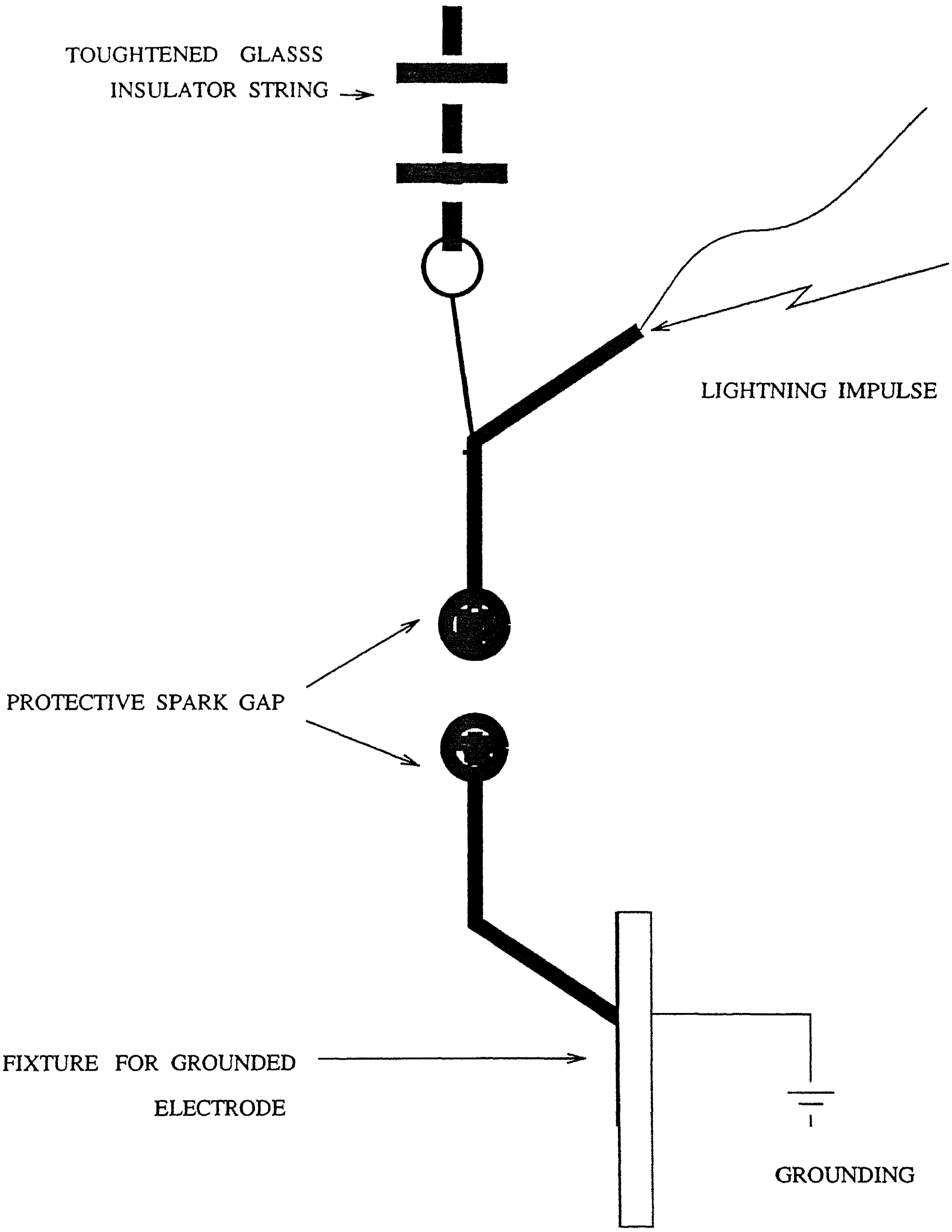


FIG 4.5 : EXPERIMENTAL SETUP FOR INVESTIGATION OF PROTECTIVE SPARK GAPS

4.3 Set-up for the Investigation of Performance of Protective Spark Gaps

The set-up used for studying the performance of the protective spark gaps is shown in Fig 4.5. The set-up is very similar to the one described in sec 4.2 2 above, except for the fact that the cloud electrode and the ground electrodes were replaced by the protective spark gap electrodes under test as shown in the fig 4.5. Since the investigations involved study of the performance of the spark gap electrodes under different conditions, the following methods were used to simulate the polluted conditions of the electrodes :-

(a) **Insulating Dust Layer** This was simulated using a layer of Kaolin suspension in water which was sprayed on the surface of the test electrodes and dried. Efforts were made to keep this layer deposition as uniform as possible.

(b) Thick Adherent Insulating Layer. This was simulated by using a thin coating of liquid resin which was then dried to form a hard insulating layer. The resin was applied with the help of a brush on the electrode tips and again care was taken to ensure a smooth and uniform layer.

(c) Partially Corroded with a layer of Salt Deposition. This was achieved by abrasion of the electrodes to the extent to partially damage the zinc coating and than exposing it to especially formulated sea water fog in a fog chamber for 15 days.

(d) Fully Corroded with a Thick Layer of Rust. This was achieved after removing the protective zinc layer by getting it dissolved in diluted Sulphuric acid and then exposing it to salt fog for 15 days.

Since the aim was to study the effect of different conditions of the spark gap electrodes, different spark gap electrodes were exposed to different treatments to help comparison of the effect of the degree of deterioration on the performance.

4.3.1 A total of three pairs of spark gap electrodes were investigated. They were 8 mm rod, 12 mm rod and 40 mm spherical electrodes. The first was subjected to kaolin and resin treatment, second one to resin and partial corrosion (see sec 4.3 (c)) and the last one to fully corroded state (see sec 4.3 (d)). This could be achieved with the help of the Defence Materials and Stores Research and Development Establishment (DMSRDE) of the DRDO at Kanpur.

CHAPTER 5

MEASUREMENTS AND RESULTS

5.1 Introduction

As stated earlier, the purpose of this work is two folds, that is, -

- To investigate the most suitable shape of the air terminal for of a lightning conductor in order to attract a lightning stroke.
- To investigate the effect of atmospheric pollution and consequently that of corrosion on the performance of the protective spark gaps with lightning impulse.

In view of the above, the experimental set up and the procedure adopted was such that a qualitative assessment could be carried out. This was essential as the behaviour of atmospheric air varies greatly with the variation in its temperature, pressure and humidity. Since the breakdown of air with lightning impulse is a statistical phenomenon, any measurement would be valid only under the conditions it was made and may not be repeated exactly the same way again. Hence efforts were made to study the trends and draw useful conclusions from the results.

The investigations were performed over a prolonged period and under varying atmospheric conditions, it was necessary to make corrections for temperature, humidity and pressure of air to the measured results as per IS:2071 (Part I)-1974 for a valid comparison. /17/. A computer programme was developed to do the same.

These corrections are more applicable to the investigations related to the protective spark gaps since the aim was to study the change in performance of the gap under different conditions of the electrode (clean, polluted and corroded) and these experiments were performed over a long period with considerable variation in the atmospheric conditions. The experimental work related to the air terminal electrodes was performed at a stretch of few days with hardly any variation in the atmospheric conditions.

More so, the aim here was to make a qualitative assessment to select the best shape of the air terminal.

The 50 % breakdown voltage (U_{b-50}) was measured using the ' up down ' method as suggested in IEC 60-1 /18/. It is given by ,

$$U_{b-50} = \frac{\sum U_i N_i}{\sum N_i}$$

Where , U_i is the voltage magnitude applied

N_i is the no. of times U_i was applied

$\sum N_i$ is >= 30 , and U_i is varied up/down by 3% depending on whether a breakdown took place or not

5.2 Measurement and Test Results of the Investigations on the Shape for the Air Terminal of a Lightning Conductor .

This work can be regarded as a sequel to the investigations performed by R Sawhney /4/ at IIT Kanpur in April 93 for his M Tech thesis. In his work the investigations were made for gaps varying up to maximum of 15 cm. On making an effort to understand the results obtained in his work more closely, it could be observed that,

(a) For a certain combination of the electrodes, the field configuration for the gap distance investigated was a weakly nonuniform field whereas the field in actual atmospheric conditions is extremely nonuniform. The breakdown characteristics of air varies greatly with the type of field. Care was therefore taken to perform this work strictly under extremely nonuniform field conditions.

(b) The earlier work was carried out indoors for small gap distances which could not have simulated the natural process of a lightning strike correctly. Hence outdoor investigations at longer gap distances was proposed to be carried out.

(c) The statistical time lag, which constitutes a very important parameter for comparing any two air terminal shapes (see sec 3.3.3)

was not investigated in the earlier work. Due consideration was therefore given to this parameter in the present work

(d) Due to least adjustment problems in the test equipment, U_{b-100} breakdown voltages were measured for different electrodes in the earlier work. Efforts were made to determine U_{b-50} values for the purpose of comparison of different shapes of air terminals in this work.

Efforts were made to overcome these limitations and arrive at a more realistic assessment of the most suitable shape of the air terminal.

5.2.1 Procedure Adopted

First, the investigations were carried out at the UHV Research lab of CPRI at Hyderabad . On studying the results obtained at the UHV Research lab of CPRI, Hyderabad need was felt to verify the same in small gaps at IIT Kanpur also. At both the places the general procedure of the experimental work adopted was the same. The work was carried out in two phases, namely :

Phase I -

- Determination of U_{b-50} for individual electrodes (air terminals) for varying gap distances using negative polarity li.
- Determination of Statistical time lag (T_s) for all the cases mentioned above.

Phase II-

All electrodes which exhibited similar breakdown performance were placed together in small groups and impulse voltage of magnitude higher than U_{b-100} of all the electrodes investigated for that gap was applied. The strikes on various electrodes were physically observed and counted. This ' *preferential strike test'* should undoubtedly indicate the best air terminal.

5.2.2 Results of the Investigations carried out at UHV Research lab of CPRI at Hyderabad.

Fig 5.21(a) shows the variation of the negative polarity li breakdown voltage (U_{b-50}) with gap distance. As can be seen, these experiments were

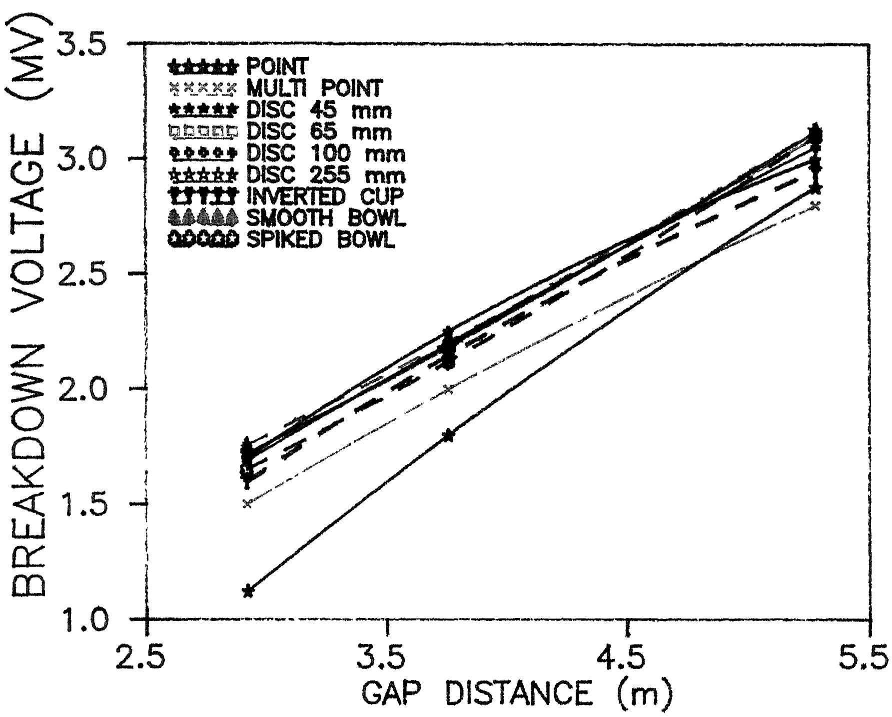


FIG 5.21 (a): BREAKDOWN VOLTAGE (Ub 50) FOR LONG GAPS USING NEGATIVE LI IMPULSE VOLTAGE FOR DIFFERENT ELECTRODES (AIR TERMINALS)

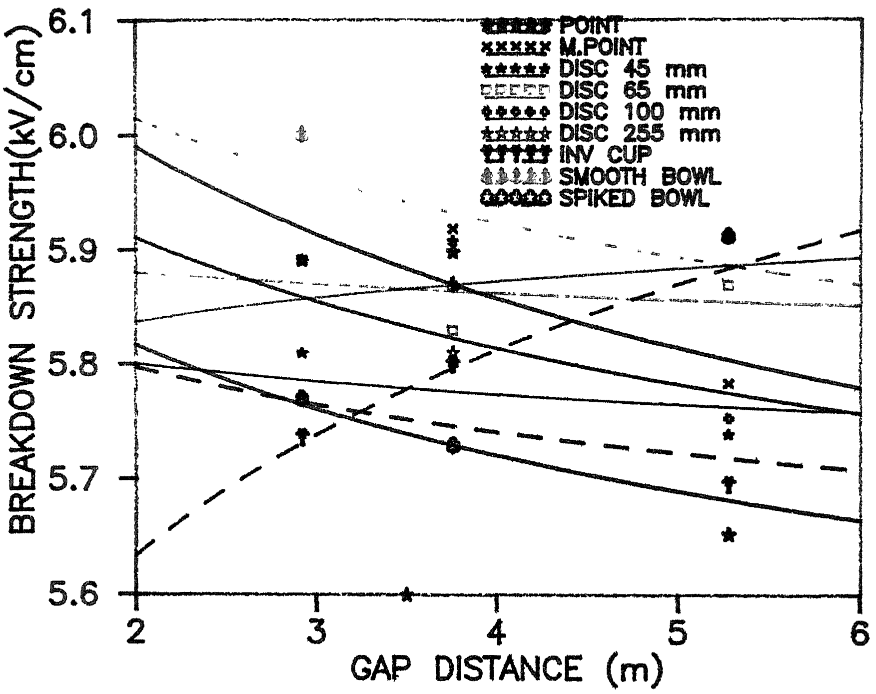


FIG 5.21(b): BREAKDOWN STRENGTH OF AIR IN LONG GAPS UNDER NEGATIVE LI IMPULSE FOR DIFFERENT ELECTRODES (AIR TERMINALS)

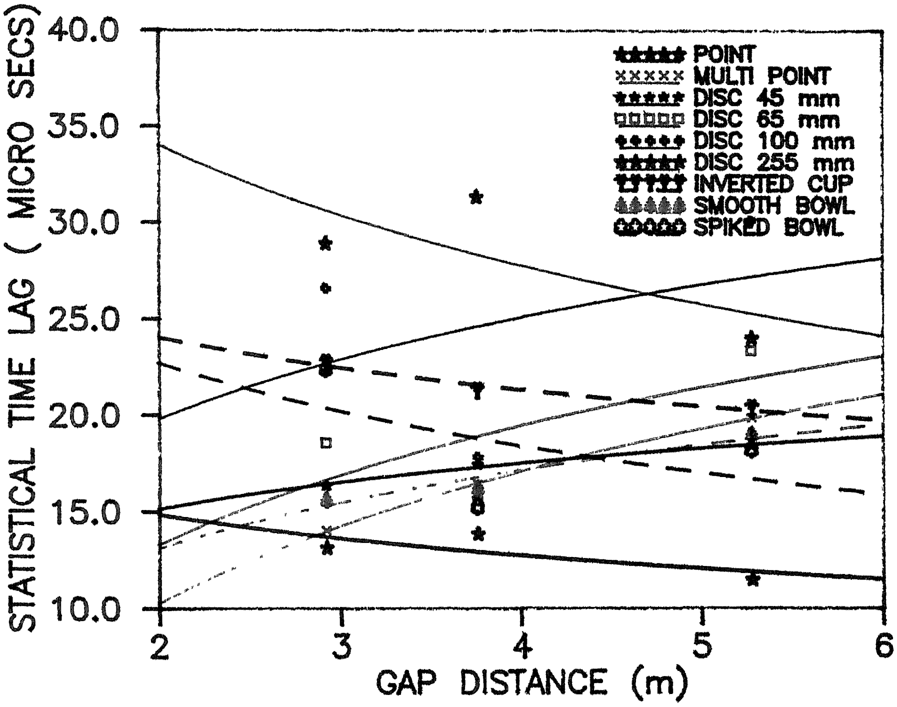
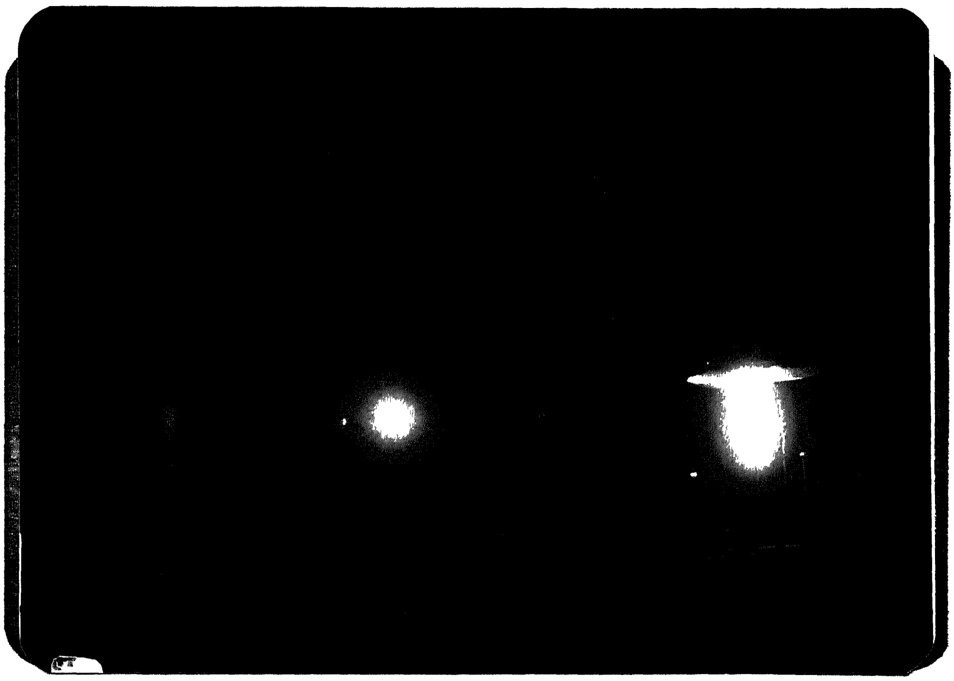


FIG 5.21(c): STATISTICAL TIME LAG FOR LONG GAPS USING NEGATIVE LI IMPULSE FOR DIFFERENT ELECTRODES (AIR TERMINALS)



PHOTOGRAPH 5: RETURN STROKES SEEN FROM POINT, MULTI POINT AND SPIKED ELECTRODE.

performed for the gap distance settings between 2.75 and 5.3 m. The lower limit of the gap distance was because of the minimum voltage which could be generated by the impulse generator. However, the longest gap distance with which the experiments could be performed was limited due to the surface discharge problems with the polypropylene ropes used for suspending the HV electrodes from the grounded support structure. Wet and humid conditions severely deteriorated the tracking resistance of the ropes leading to flashovers towards the supporting mock up tower instead of the air terminals under test. Fig 5 21(b) shows the variation of the breakdown strength of air with increasing gap distance for all the electrodes investigated.

The following conclusions can be deduced :-

(a) For the Point electrode the breakdown strength is measured to be minimum. The difference in breakdown voltages between different electrodes narrowed down as the gap distance was increased.

(b) All other electrodes exhibited breakdown voltages in a narrow range of each other (with in ± 3% experimental error permitted). Thus their relative performance based on this parameter is indistinguishable.

(c) Similar trends can be seen in the variation of the average breakdown strength of air.

(d) A larger surface area of the electrode did not result in lowering of the breakdown voltage or the strength .

Fig 5.21(c) shows the variation of the statistical time lag T_s for U_{b-50} voltages with increasing gap distance for the electrodes tested. As already discussed , the electrode exhibiting a lower T_s would generally indicate to be a preferred one. Here again, the Point electrode showed the lowest T_s. This results together with the lower U_{b-50} and E_b clearly indicates that the Point electrode would attract the lightning stroke more. Lower T_s shown by larger area electrodes like the inverted bowl is due to their higher breakdown voltages. This is due to the fact that T_s varies inversely to the applied voltage.

These conclusions were then physically verified by the ' preferential strike test'. During the test the relative positions of the electrodes was interchanged to eliminate any effect due to the position and placement of

the electrode themselves. The results of these tests are tabulated below:-

Se. No	Electrodes Used	% of Hits
1.	Point Disc 45 mm ϕ	70 30
2.	Point Disc 65 mm ϕ	100 10 *
3.	Point Disc 100 mm ϕ	100 0
4.	Point Inverted Bowl 255 mm ϕ (spiked)	90 10
5.	Point Disc 255 mm ϕ	100 0
6.	Point Inverted bowl 255 mm ϕ (smooth)	100 0
7.	Point Multi point	70 40 *
8.	Point Multi point Inverted bowl spiked 255 mm ϕ	100 0 0
9.	Point (Height reduced by 5 cm) Multi point Inverted bowl spiked 255 mm ϕ	30 60 10

* Few Simultaneous hits to both the electrodes

The results of the ' preferential strike test ' clearly reveals that the point is most suitable shape of air terminal for the lightning conductor. In some cases simultaneous strikes on more than one electrode were observed. But the intensity of light in the return stroke channel in case of the Point electrode was found to be more intense in all such cases Photo 5 shows distinct return strokes developed from the Point, multi point and the spiked inverted bowl electrodes placed together for the ' preferential strike test'. It can be seen clearly that an upward return stroke from the point electrode bridged the gap and caused breakdown where as the return strokes from the other two electrodes have not been able to

bridge the gap as they were of a lower intensity. In other words it can be said that they have not been able to attract the downward leader of the lightning stroke to the extent to accomplish the li strike. The stronger return stroke seen from the multi point electrode can be inferred to give a better performance of this electrode over the spiked electrode .

Fig 5.21(c) shows that the point electrode requires the lowest T_s compared to multi point electrode whereas spiked electrode requires the longest T_s. An electrode with lower T_s as well as lower U_b should be the most suitable shape for the air terminal. It can be concluded that lowest T_s in case of the point electrode enabled to initiate a stronger upward leader (return stroke) earlier than others and achieve a breakdown before other electrodes.

5.2.3 Results of the Investigations carried out at HV lab of IIT Kanpur

The investigations carried out at IIT Kanpur were desired to be under similar field conditions as at Hyderabad. The experimental set up in this smaller indoor laboratory was a scaled down model of the one used at CPRI, Hyderabad. The gap distance ranged from 15 to 36 cm due to the limitations of the voltage generated by the Impulse generator and the limited clearances from the walls available. The experiments were performed strictly in extremely non uniform field conditions.

Fig 5.22 (a) and Fig 5.22 (b) shows the variation of the U_{b-50} and the average breakdown strength of air, E_b, with increasing gap distance for different electrodes. The results are quite similar to the one measured at CPRI, Hyderabad except for a few differences observed as following:-

(a) Instead of the Point electrode, with the inverted spiked bowl the lowest U_b and hence E_b were measured. With the point electrode the neat higher characteristics was measured. The difference in U_{b-50} narrows down with increasing gap. This shows diminishing effect of the small spikes on the surface of the spiked electrode as the gap was increased. This could happen due to the increasing enveloping effect of the number of individual spikes at longer gap distances.

(b) With the Disc of 25 mm ϕ the highest U_b and hence E_b, were measured unlike in case of Smooth inverted bowl electrode (255 mm ϕ) in meter gap distance.

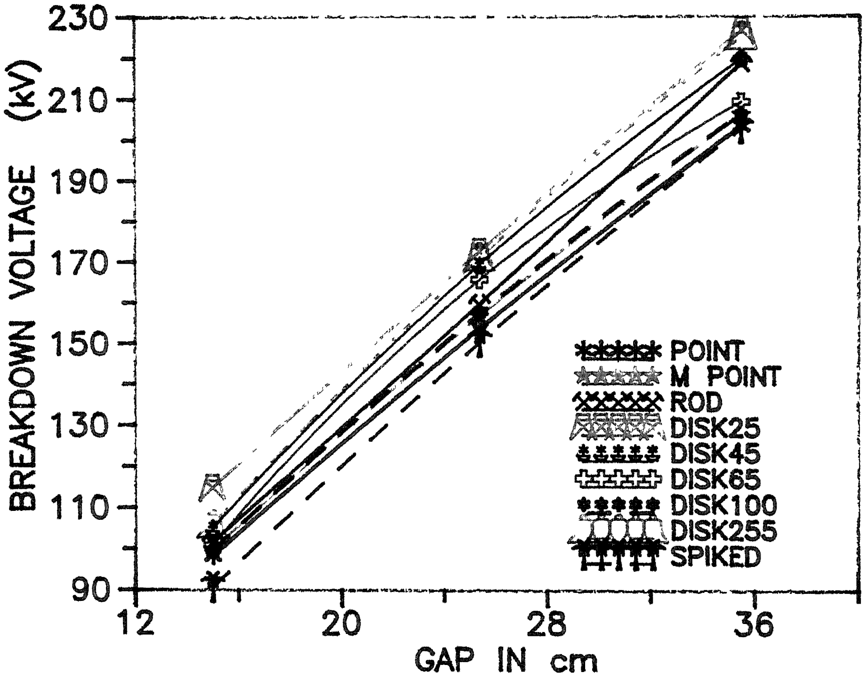


Fig 5.22(a):BREAKDOWN CHARACTERSTICS IN cm GAPS FOR DIFFERENT ELECTRODES NEGATIVE POLARITY LI

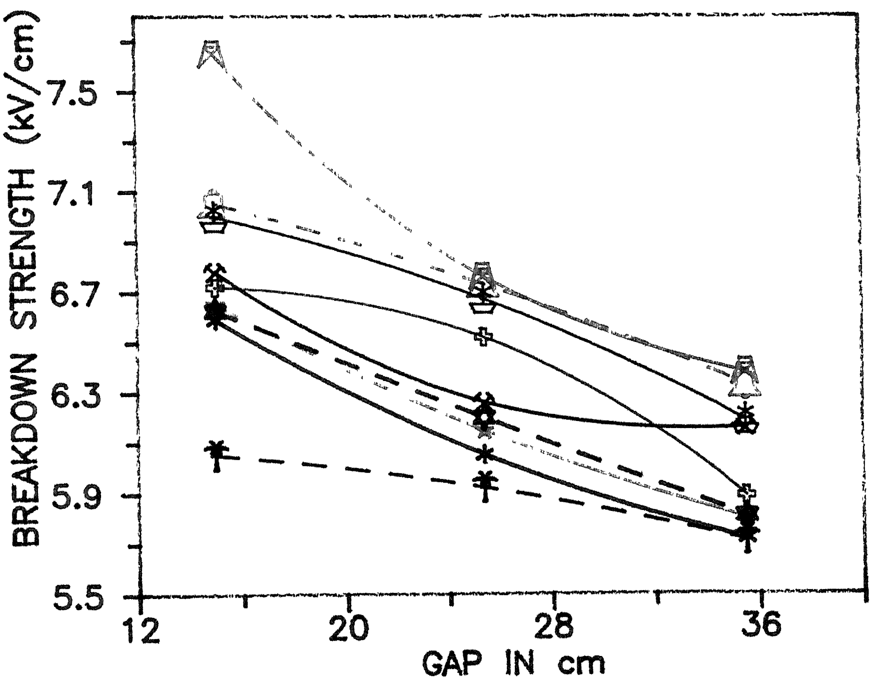


FIG 5.22(b) : BREAKDOWN STRENGTH OF AIR IN cm GAPS FOR DIFFERENT ELECTRODES NEGATIVE POLARITY LI (LEGEND AS FIG ABOVE)

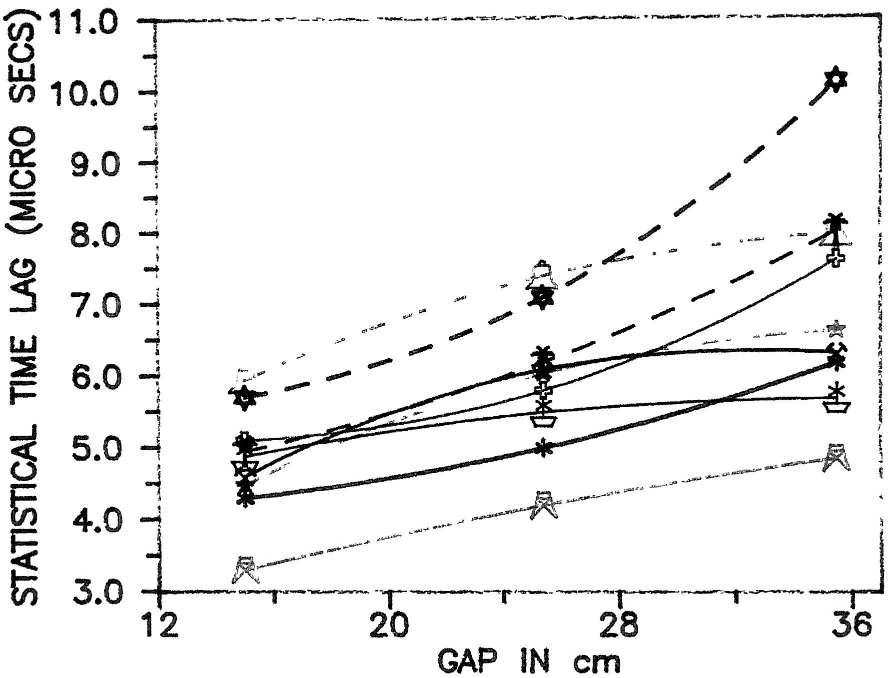


FIG 5.22(c): STATISTICAL TIME LAG IN cm GAPS FOR DIFFERENT ELECTRODES FOR NEGATIVE POLARITY LI (LEGEND AS FIG 5.22(b))

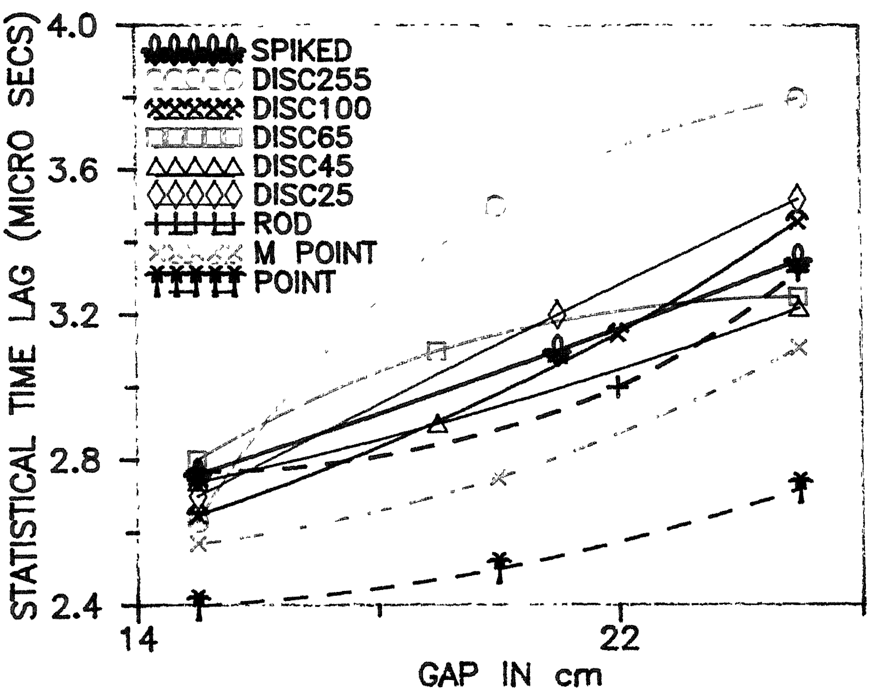


FIG 5.22(d): STATISTICAL TIME LAG IN cm GAPS FOR DIFFERENT ELECTRODES FOR THE SAME VOLTAGE APPLIED TO ALL THE ELECTRODES (NEGATIVE LI)

(c) For all other electrodes, namely Discs of 45, 65, 100 and 255 mm ϕ, multi point electrode and Rod 20 mm ϕ , U_b measured were in small range of each other but with a clear difference in U_{b-50} voltages measured as compared to meter gaps.

Fig 5 22 (c) shows the variation of statistical time lag T_s with gap distance as recorded while measuring the U_{b-50} values for different electrodes. It can be observed that for the Disc of 25 mm ϕ, T_s measured is lower than the point electrode . This can be related to the fact that for the Disc 25 mm ϕ the highest U_b was measured and T_s is inversely proportional to the magnitude of the applied voltage. The Point electrode still has the second lowest T_s in spite of having a lower U_{b-50}. Similar results were observed and shown in Fig 5.22 (d) where variation of statistical time lag T_s were measured for all the electrodes by applying the same magnitude of impulse voltageto all the electrodes. It can be clearly observed that with the point electrode measured the lowest T_s. With the spiked bowl and the disc of 25 mm ϕ a much higher T_s were measured. Thus they are likely to be less attractive in the ' preferential strike test' This was later verified by carrying out the ' preferential strike test'. The results of this test were as following:-

→ NEXT PAGE

Se. No	Electrodes Used	% of Strikes
1.	Point Disc 45 mm ϕ ,Disc 25 mm *	100 0
2.	Point Disc 65 mm ϕ,Disc 100 mm , Rod *	100 0
3.	Point Multi point	100 0
4.	Point Inverted Bowl 255 mm ϕ (spiked)	95 5
5.	Point Disc 255 mm ϕ	100 0
6.	Disc 100 mm ϕ Disc 65 mm ϕ, Disc 45 mm ϕ *	100 0
7.	Disc 65 mm ϕ Disc 45 mm ϕ	70 30
8.	Disc 65 mm ϕ ,Disc 45 mm ϕ * Disc 25 mm ϕ,	100 0

* electrodes placed one at a time with the other given electrode.

Interesting conclusions can be drawn from the above results. The Point electrode is the most suitable shape of the air terminal for a lightning conductor. On subjecting the discs of various diameters to the ' preferential strike test', the effect of the area of the grounded electrode can be clearly observed. However this effect is a limited to a certain extent and does not show itself once area is increased further.This could be due to increasing uniformity in the field introduced by the larger area. It may be relevant to mention here that the smooth inverted cups (100 mm and 125 mm ϕ) were initially tried but discarded for this test due to a very high U_b as compared to other electrodes. This can be rendered to the development of nearly weakly nonuniform field between the cloud and the inverted bowl (having no sharp edges) for the gap distance upto 36 cm.

5.3 Results of Investigation on Protective Spark Gaps

Three protective spark gap electrode pairs were investigated, they are-

(a) Hemispherical Rod-Rod gap dia 8 mm (Spark gap 1)

(b) Hemispherical Rod-Rod gap dia 12 mm(Spark gap 2)

(c) Sphere-Sphere gap dia 40 mm(Spark gap 3)

All these were subjected to both positive and negative polarity standard lightning impulse for varying gap lengths ranging from 30 mm to 350 mm. This range of gap length for the experimentation was limited by the minimum and the maximum voltage generated by the impulse generator and the other safety considerations. The following measurements and analysis by the results of the investigations were carried out:-

(a) Variation of breakdown voltage (U_{b-50}) for both positive and negative polarity (U_{b+} and U_{b-}) impulse voltage versus gap distance d, for the following conditions of the electrode:-

(i) Clean condition (U_{bc+} and U_{bc-}).

(ii) Kaolin coated simulating a well settled dust layer on the surface of the electrodes (U_{bk+} and U_{bk-}).

(iii) Resin coated, simulating a hardened insulating layer on the surface of the electrode (U_{br+} and U_{br-}).

(iv) Partially and fully corroded (rusted) condition of electrode surface (U_{bco+} and U_{bco-}).

(b) Variation of the Average Breakdown strength of air (E_{b+} and E_{b-}) with gap distance for the above mentioned cases.

(c) Variation of statistical time lag T_s with gap distance for the above mentioned cases.

(d) Percentage change of U_b from clean condition for the deteriorated condition of the electrode surface.

(e) Volt-Time characteristics of the spark gaps for various gaps for both positive and negative polarity li.

Corrections for atmospheric conditions have been applied where ever required to arrive at correct conclusions by taking into account atmospheric variation with time as per IS: 2071 (Part I)-1974.

5.3.1 Investigations on Protective Spark Gap 1 (Rod-Rod Gap diameter 8 mm)

This spark gap electrode was subjected to Kaolin and Resin treatment separately (described in sec 4.3). Fig 5.3 (a) and 5.3 (b) give the variation of U_{b+} and U_{b-} vs d for positive polarity li and negative polarity li respectively for clean condition of electrode. Both measured and corrected data has been plotted. The variation between measured and corrected data can be seen Here corrected data is generally less than the measured data. Fig 5.3 (c) compares the U_{b+} and U_{b-} after the data has been corrected. It can be clearly seen that U_{b-} is greater than U_{b+} and this difference increases with increasing gap distance or in other words the degree of nonuniformity of the electric field.

Fig 5.3 (d) shows the variation of breakdown strength of air E_{b+} and E_{b-} for positive polarity li and negative polarity li with gap distance d. The E_b varies from 16 kV/cm to 8.5 kV/cm for negative polarity li and 14 kV/cm to 8 kV/cm for positive polarity li. The steep drop in E_b in between 30 mm and 90 mm gap distance indicates a rapid transition in the degree of uniformity, η in this region. At 30 mm gap the field is closer to a weakly nonuniform field, hence a higher E_b. As the gap ,distance is increased, the field acquires the extremely nonuniform characteristics completely represented by a saturated value of E_b.

Figs 5 3 (e) and (f) gives the variation of U_{bk} (Kaolin coated) , U_{br} (resin coated) with increasing gap distance d for both positive and negative polarity li. Figs 5.3 (g) and (h) show the percentage variation in U_b from the clean conditions. Normal correction factors have been applied for considering the different atmospheric conditions. Following conclusions can be drawn from these figures :-

(a) The breakdown voltage U_b for polluted condition of electrodes is initially higher than that for clean condition of the electrodes for smaller gap distance. However it gradually falls below the clean condition breakdown voltage once the gap is increased. U_b for polluted condition of electrode seems to be higher than that for clean condition of electrode when the field is closer to weakly nonuniform, that is, no

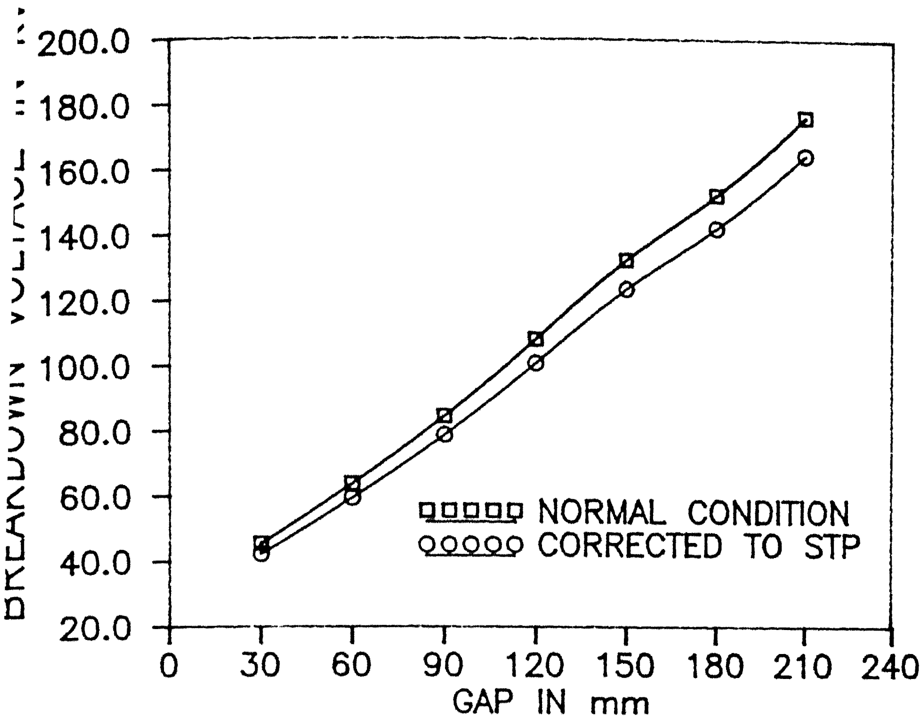


Fig 5.3(a): BREAKDOWN VOLTAGE (Ub 50) POSITIVE POLARITY AT NORMAL ATMOSPHERIC CONDITIONS AND AT STP CLEAN CONDITION OF ELECTRODE (ROD GAP 8 mm DIA)

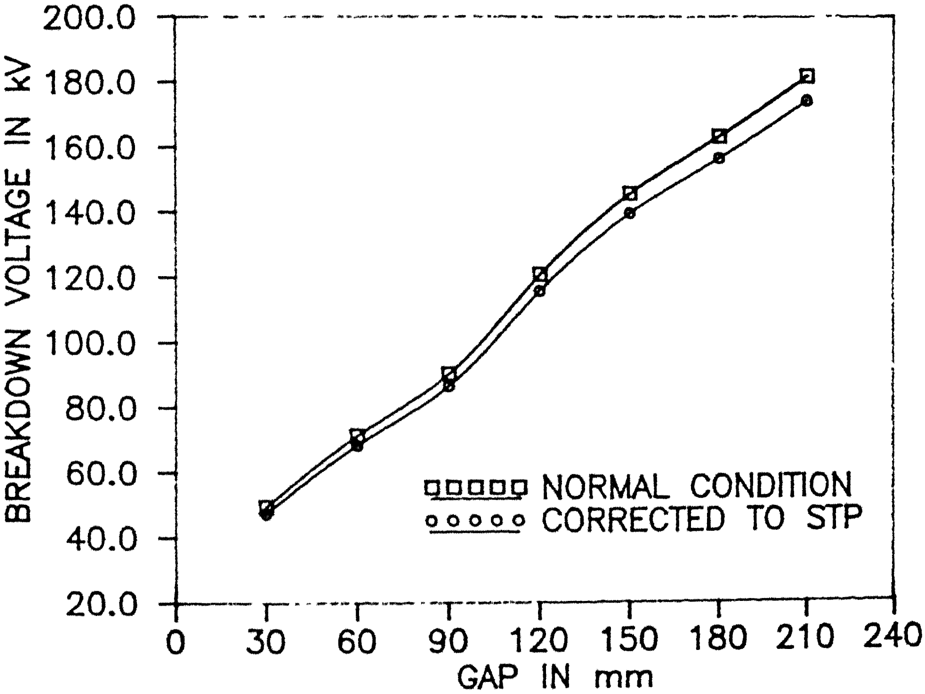


Fig 5.3(b): BREAKDOWN VOLTAGE (Ub 50) NEGATIVE POLARITY AT NORMAL ATMOSPHERIC CONDITIONS AND AT STP CLEAN CONDITION OF ELECTRODE (ROD GAP 8 mm DIA)

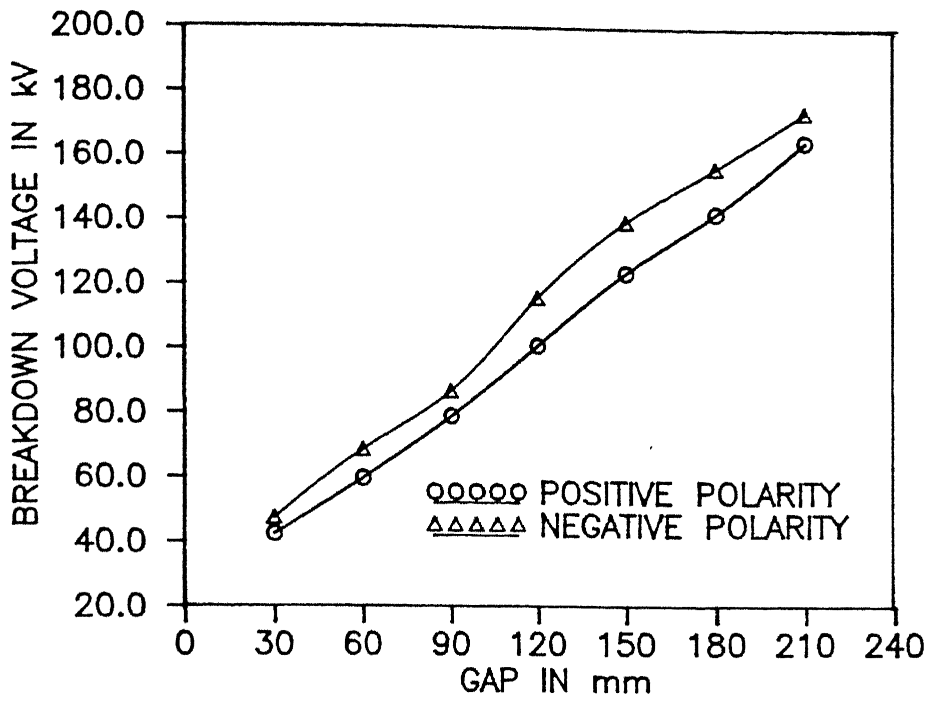


Fig 5.3(c): BREAKDOWN VOLTAGE (Ub 50)
FOR POSITIVE AND NEGATIVE POLARITY AT STP
CLEAN CONDITION OF ELECTRODE (ROD GAP 8 mm DIA)

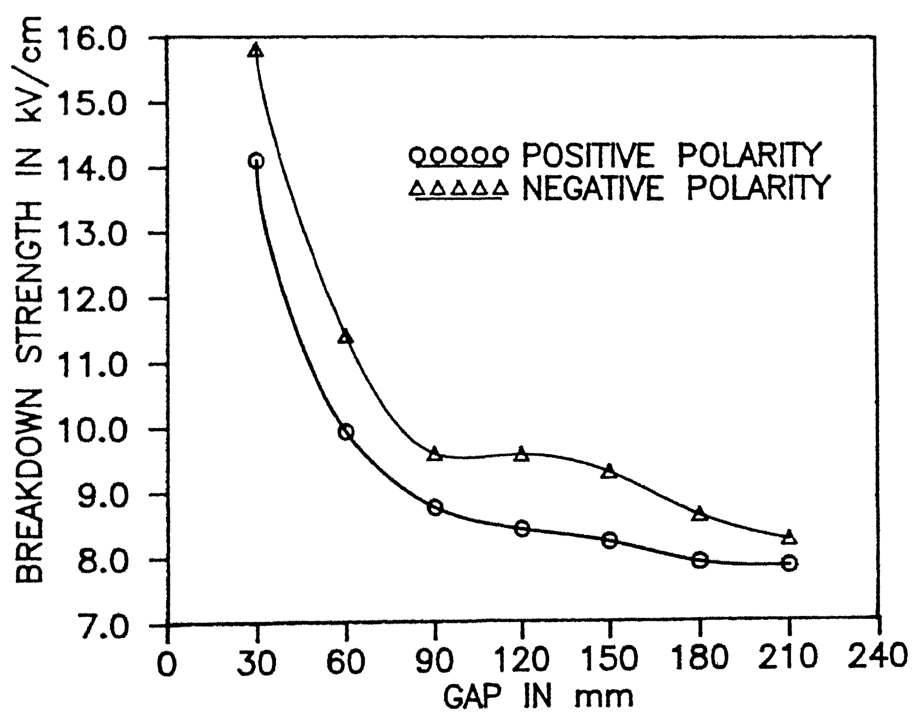


Fig 5.3(d): BREAKDOWN STRENGTH OF AIR
FOR POSITIVE AND NEGATIVE POLARITY AT STP
CLEAN CONDITION OF ELECTRODE (ROD GAP 8 mm DIA)

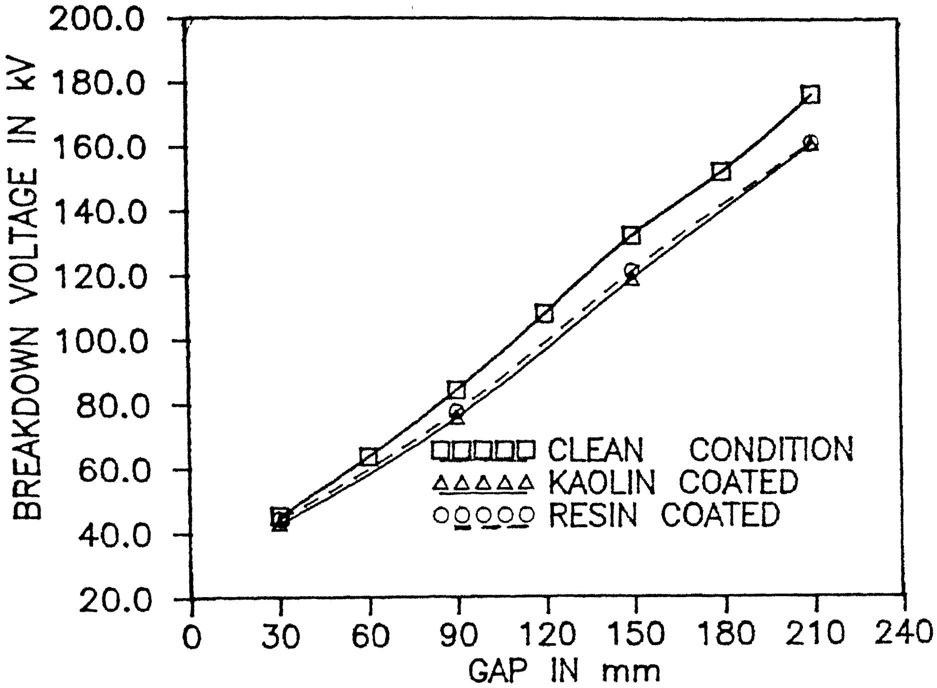


Fig 5.3(e): COMPARISION OF BREAKDOWN VOLTAGE POSITIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR ROD GAP 8 mm DIA CORRECTED TO STP CONDITIONS

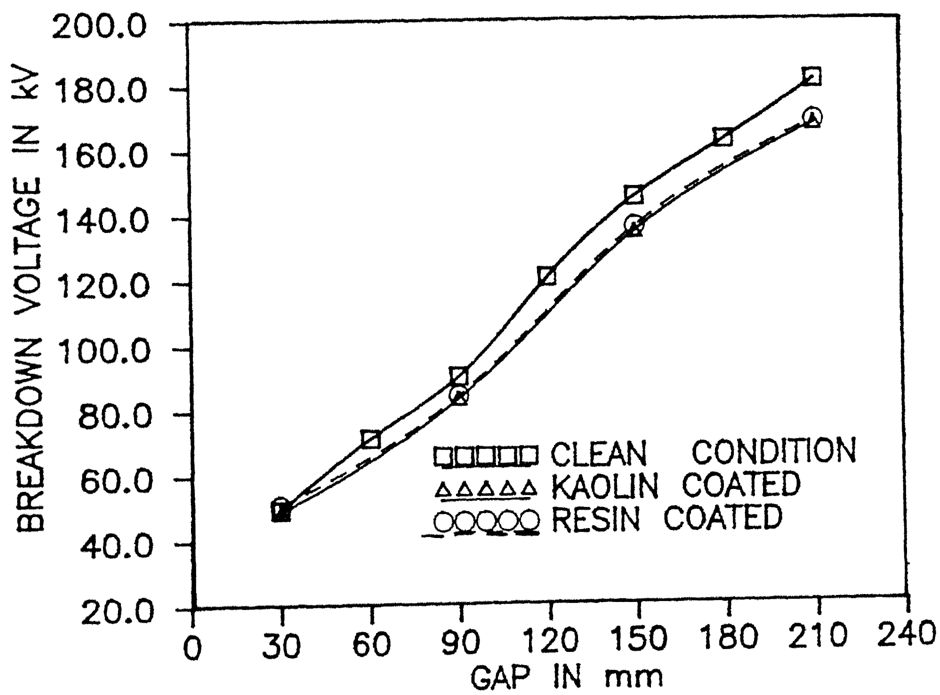


Fig 5.3(f): COMPARISION OF BREAKDOWN VOLTAGE NEGATIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR ROD GAP 8 mm DIA CORRECTED TO STP CONDITIONS

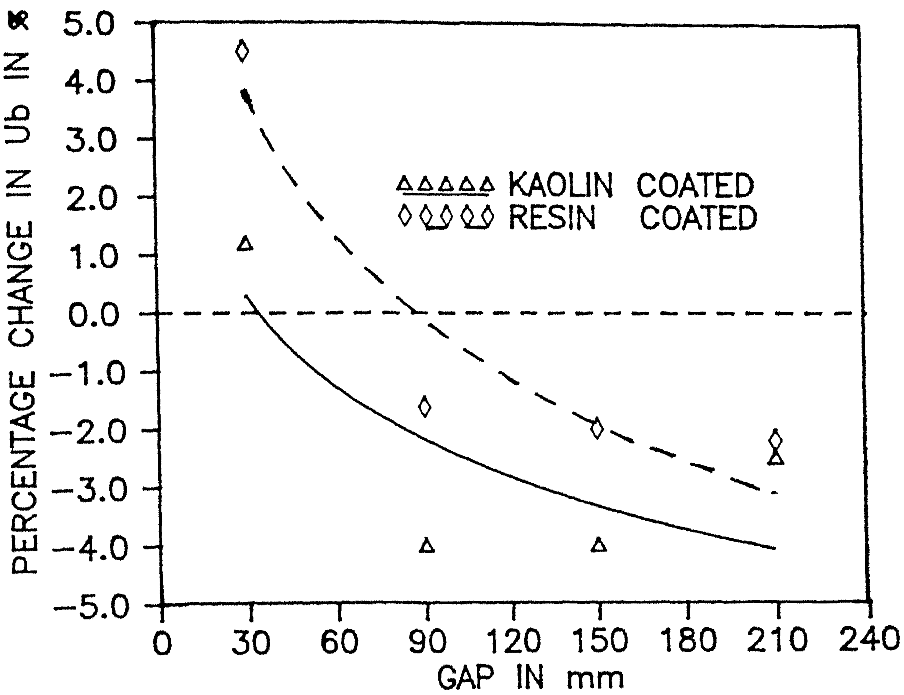


Fig 5.3(g): PERCENTAGE CHANGE IN BREAKDOWN VOLTAGE POSITIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE COMPARED TO CLEAN CONDITION FOR ROD GAP 8 mm DIA CORRECTED TO STP CONDITIONS

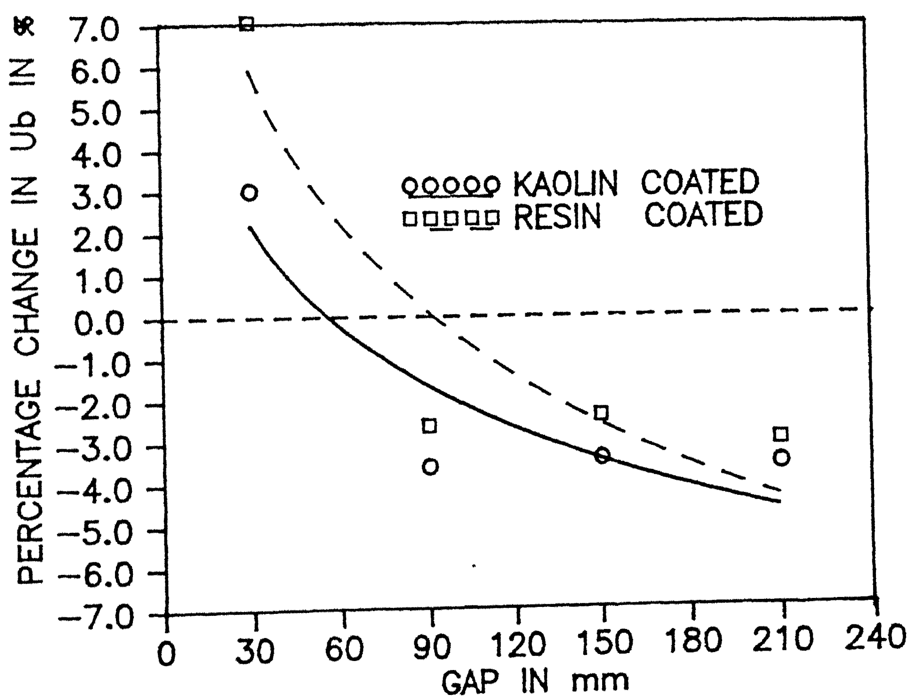


Fig 5.3(h): PERCENTAGE CHANGE IN BREAKDOWN VOLTAGE NEGATIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE COMPARED TO CLEAN CONDITION FOR ROD GAP 8 mm DIA CORRECTED TO STP CONDITIONS

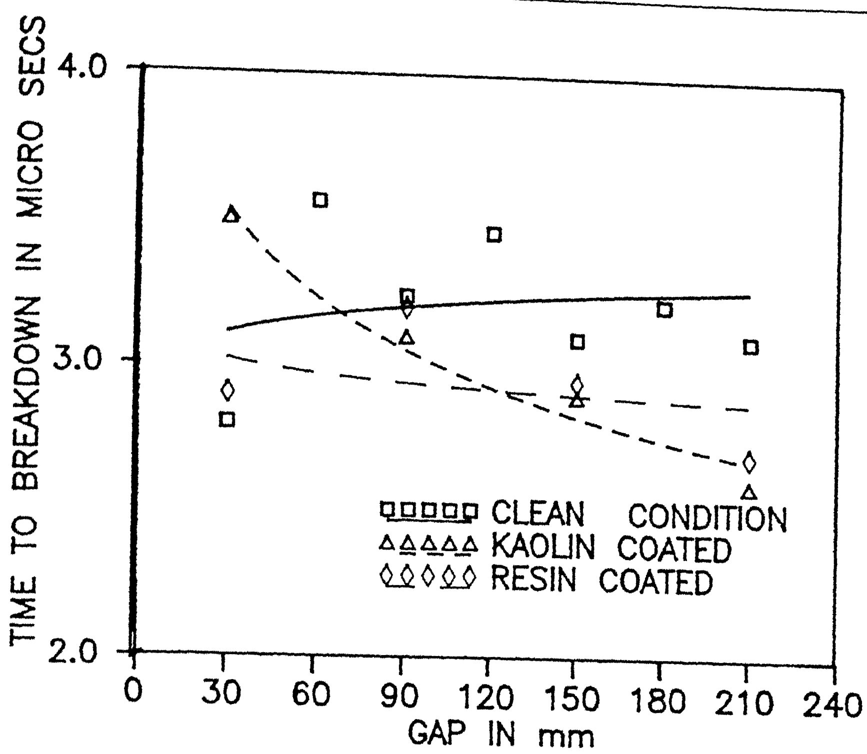


Fig 5.3(j): COMPARISION OF BREAKDOWN TIME FOR POSITIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR ROD GAP 8 mm DIA

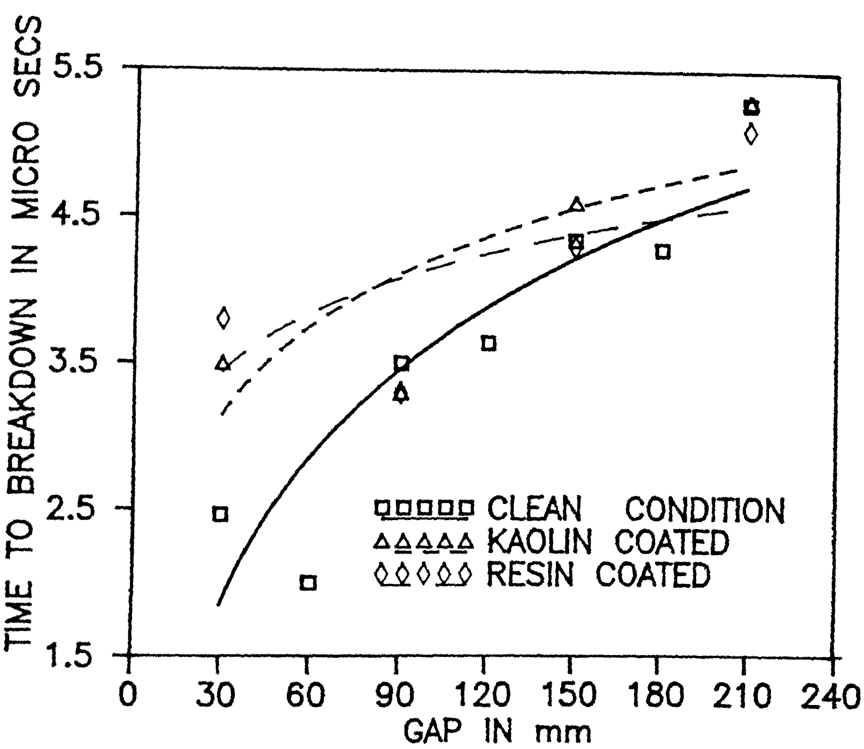


Fig 5.3(k): COMPARISION OF BREAKDOWN TIME FOR NEGATIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR ROD GAP 8 mm DIA

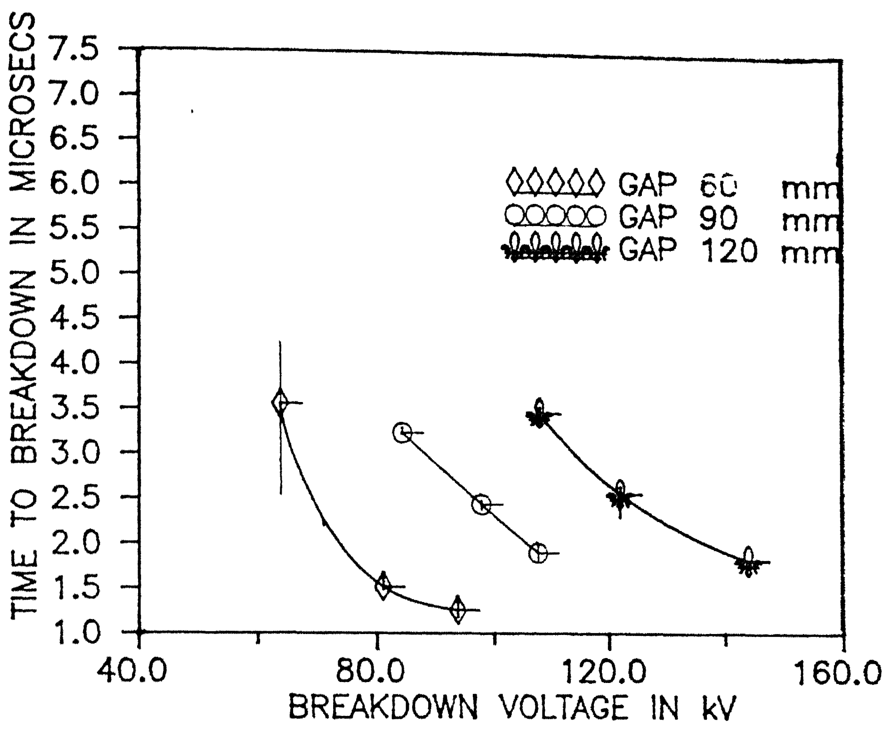


FIG 5.3(l) : VOLT– TIME CHARACTERSTICS
1.2/50 IMPULSE VOLTAGE SPARK GAP DIA: 8 mm
FOR GAP 30 mm TO 120 mm POSITIVE POLARITY
CLEAN CONDITION OF ELECTRODES

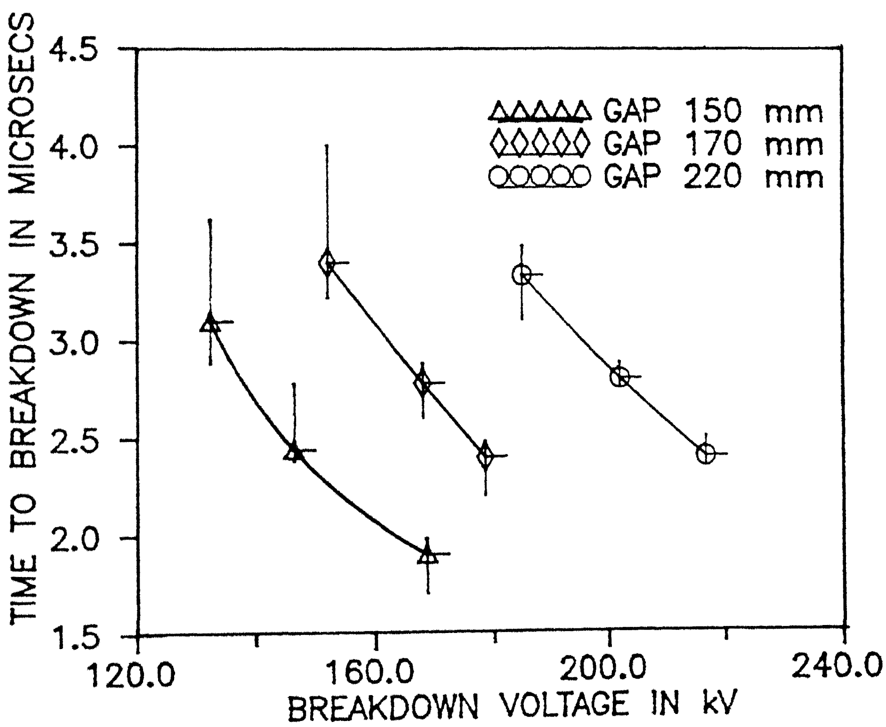


FIG 5.3(m):VOLT– TIME CHARACTERISTICS
1.2/50 IMPULSE VOLTAGE SPARK GAP DIA: 8 mm
FOR GAP 150 mm TO 220 mm POSITIVE POLARITY
(CLEAN CONDITION OF ELECTRODES)

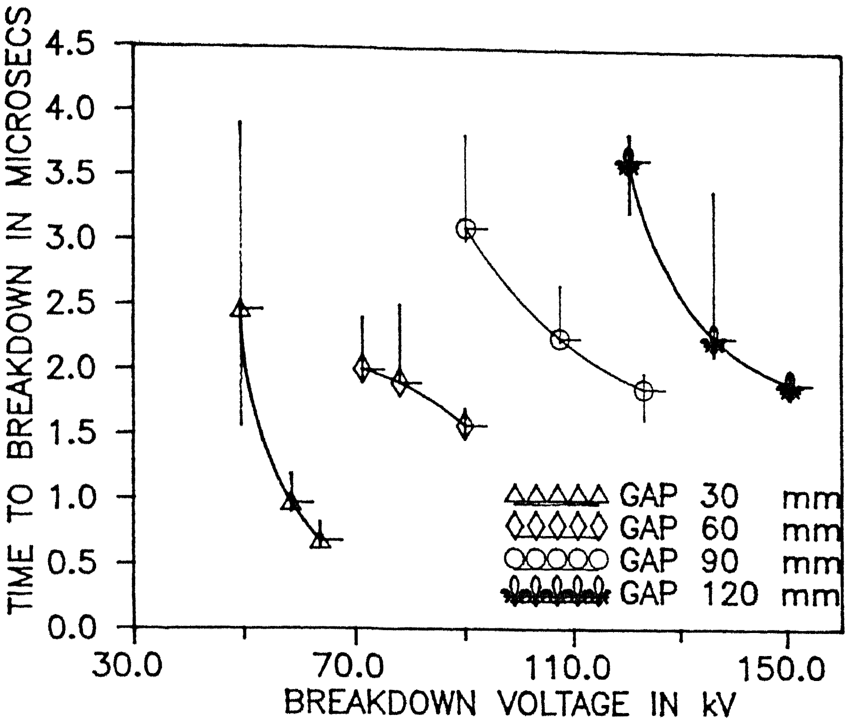


FIG 5.3(n) : VOLT– TIME CHARACTERISTICS
1.2/50 IMPULSE VOLTAGE SPARK GAP DIA: 8 mm
FOR GAP 30 mm TO 120 mm NEGATIVE POLATITY
CLEAN CONDITION OF ELECTRODES

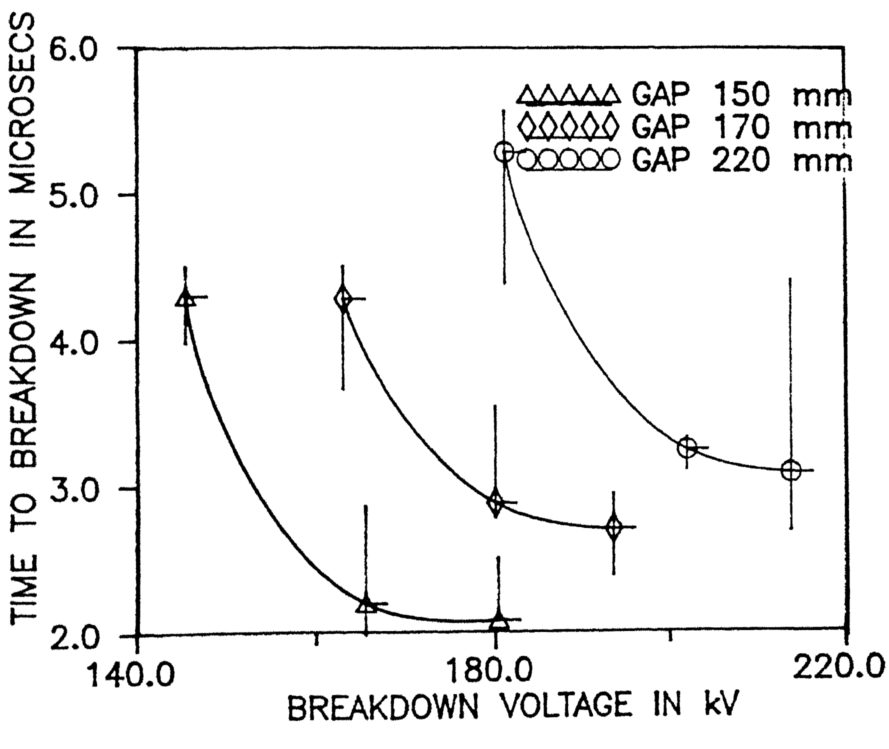


FIG 5.3(o) : VOLT– TIME CHARACTERSTICS
1.2/50 IMPULSE VOLTAGE SPARK GAP DIA: 8 mm
FOR GAP 150 mm TO 210 mm NEGATIVE POLARITY
(CLEAN CONDITION OF ELECTRODES)

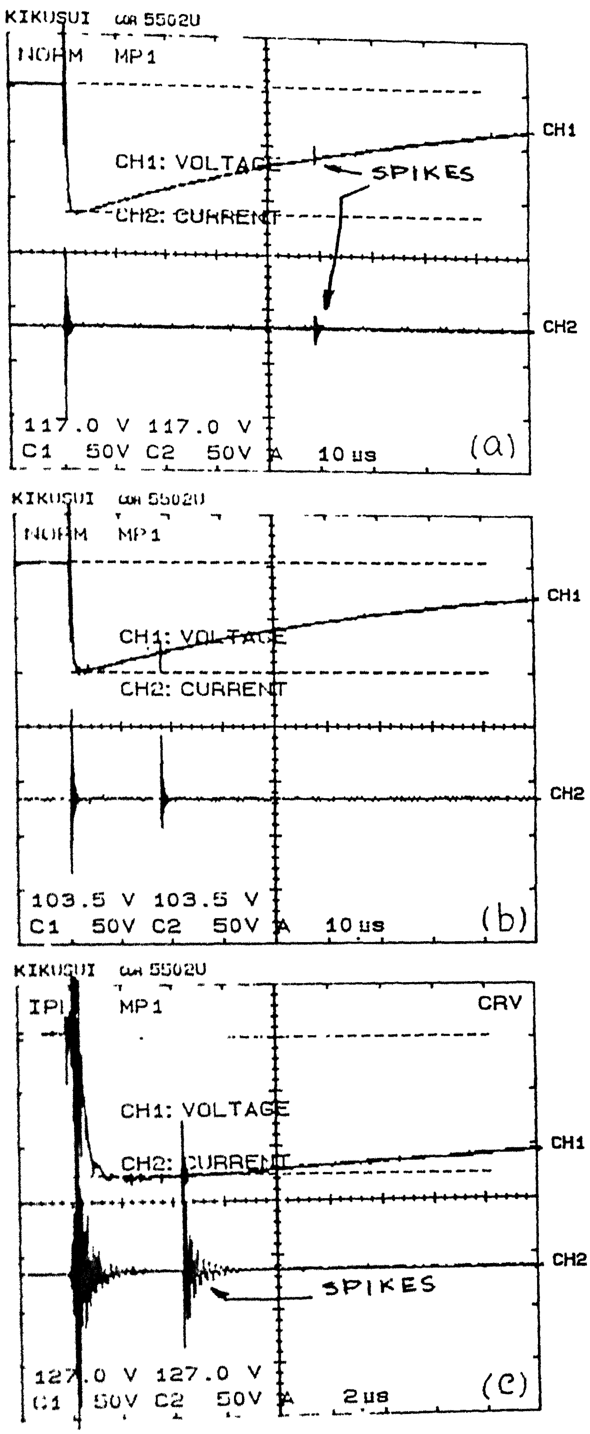
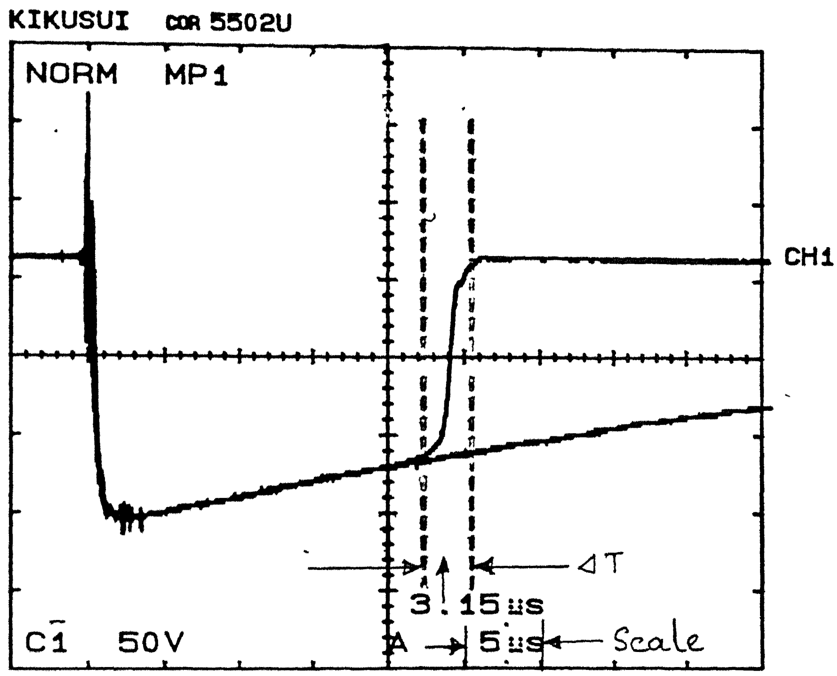


FIG 5.3 (P): OSCILLOGRAMS SHOWING SPIKES ON THE VOLTAGE AND CURRENT WAVEFORMS INDICATING PD



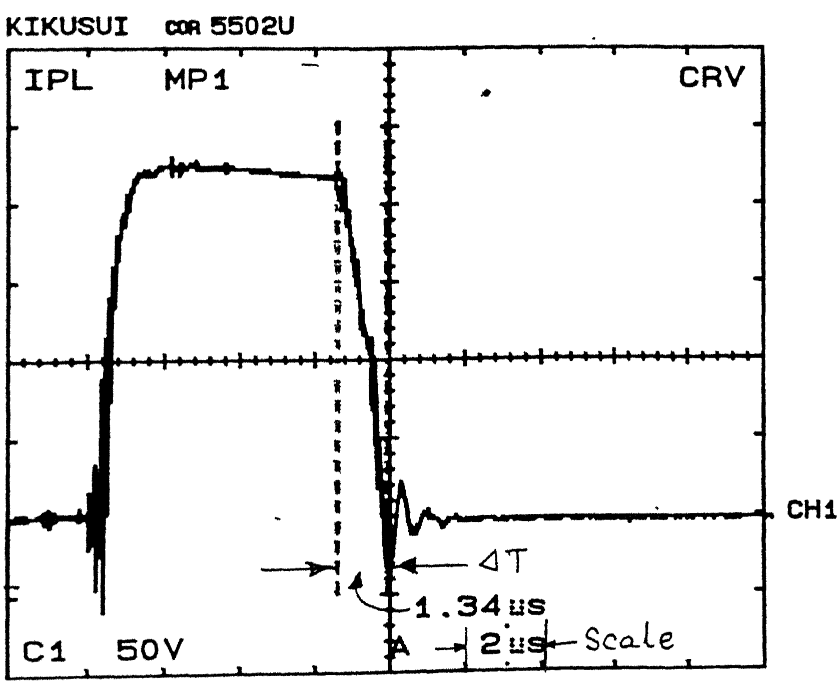


FIG 5.3 (Q): OSCILLOGRAMS SHOWING MORE TIME REQUIRED BY NEGATIVE IMPULSE THAN POSITIVE POLARITY IMPULSE TO BRIDGE THE SAME GAP DISTANCE DURING BREAKDOWN.

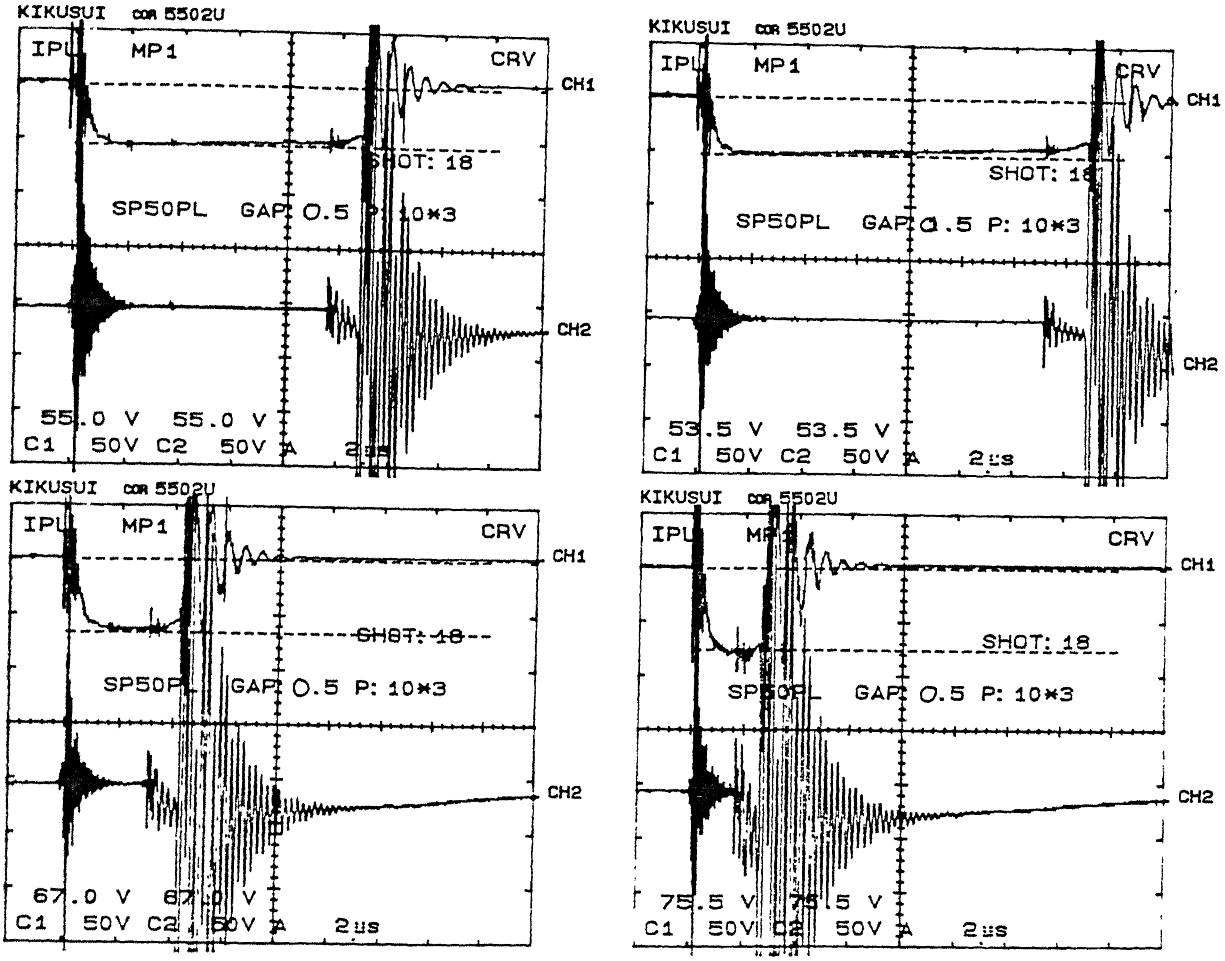


FIG 5.3 (R): OSCILLOGRAMS SHOWING LOWER TIME REQUIRED FOR BREAKDOWN AT HIGHER MAGNITUDE OF THE APPLIED LIGHTNING IMPULSE

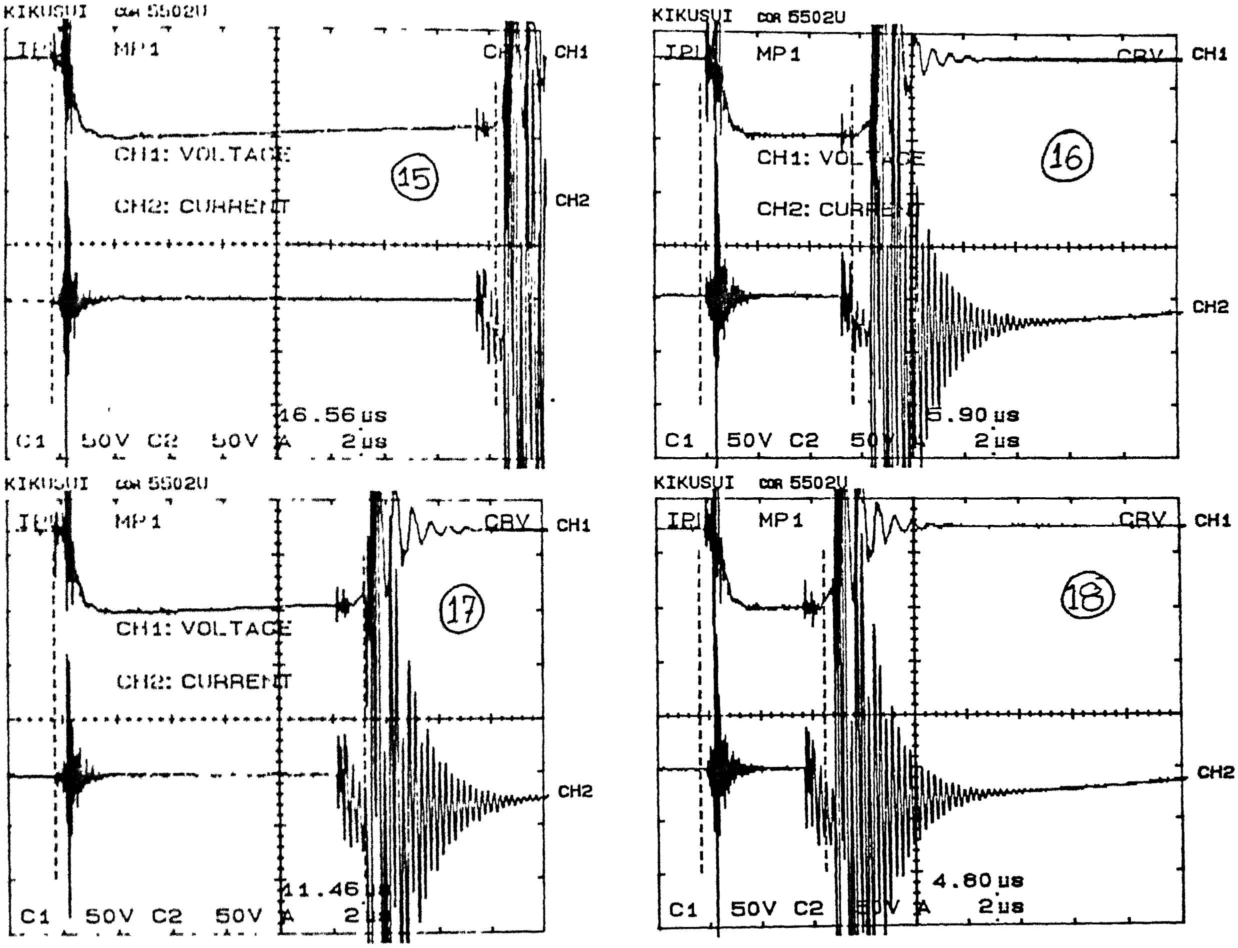


FIG 5.3 (S): OSCILLOGRAMS SHOWING DIFFERENT TIME REQUIRED FOR BREAKDOWN FOR THE SAME MAGNITUDE OF THE APPLIED IMPULSE VOLTAGE AND THE SAME GAP

substantial partial discharge (PD) could precede the breakdown especially with the li voltage. In extremely nonuniform fields when PD preceded the breakdown, there is a likelihood of the rupture of the thin coating applied on the electrode surface. Also voids and air pockets trapped will provide regions of very high fields. There is also a possibility of tracking. This assists in initiating breakdown at lower voltage itself due to the presence of the initiatory particles provided by the evaporating film by PD.

(b) On comparing the U_b for kaolin coating and resin coating It can be seen in case of both positive and negative polarity li, that the U_b for resin coating is higher than for kaolin coating for all gaps. Difference in U_b however reduces gradually with increasing gap. This may be due to the fact that the resin layer is more uniform, homogeneous , hard and adherent than the loose kaolin layer and offers more resistance to rupture due to PD.

The damage of the pollution layer applied can be verified from the voltage and current waveforms recorded by the oscilloscope on application of li. Fig 5.3 (p) shows such oscillograms having PD spikes on the voltage and current wave tails. In spite of the best effort the layers applied were not very uniform in finish and thickness due to practical constraints. The loose particles and the surface irregularities must also have helped in reducing the breakdown voltage by enhancing the electric field at the irregularities thus formed. The loose particles and the occurrence of PD together ensure the presence of the initiatory electrons to start the breakdown process at an early stage.

Figs 5.3(j) and (k) compare the statistical time lag T_s or the total time taken to breakdown for different conditions of the spark gap with both positive and negative polarity li. It can be observed that T_s gradually reduces as the gap is increased. A lower t_s for polluted condition of electrode in case of positive polarity li indicates the presence of initiatory particles introduced by application of the insulating layer. In case of negative polarity li, the t_s for polluted condition of electrode is slightly higher than for clean condition for small gaps but this difference in t_s reduces as the gap is increased. It can be seen that the time required for breakdown to take place with the pollution layer is longer with negative

polarity li than with positive polarity li as compared to clean condition of the electrode. This is due to the phenomenon of space leader typical of negative polarity impulse breakdowns. This has been mentioned earlier in chapter 2. Oscillograms in Fig 5.3 (q) shows the higher time required for negative polarity li than positive polarity li for the same electrode and gap.

Figs 5.3 (l) to (o) shows the volt-time characteristics of the spark gap for different gap distances for both positive and negative polarity li . The following observations can be made :-

(a) Statistical time lag T_s is inversely proportional to the applied voltage. This can be seen in Fig 5.3(r) which shows that lower time is required for breakdown for higher magnitude of applied li for the same gap distance.

(b)The time lag T_s is statistical in real sense and has a wide range. Mean values of T_s has been used for plotting these characteristics. Different t_s can be recorded for the same magnitude of li applied for the same gap. This can be clearly seen in Fig 5.3 (s) showing oscillograms recorded.

.5.3.2 Investigations on Protective Spark Gap 2 (Rod-Rod Gap diameter 12 mm)

This spark gap was subjected to Resin treatment and also to partial corrosion by subjecting the surface to abrasion with an abrasive to damage its galvanising layer and then kept in a sea water salt fog chamber for 15 days as described in sec 4.3. A thin layer of salt got deposited on the surface along with patches of rust.

Fig 5.4 (a) and 5.4 (b) give the variation of U_{b+} and U_{b-} vs d for both for positive and negative polarity li respectively for clean condition of electrode. Both the measured and the corrected data have been plotted showing the difference distinctly. The corrected U_b values are generally less than the measured one. Fig 5.4 (c) compares the U_{b+} and U_{b-} values. It can be clearly seen that U_{b-} is greater than U_{b+} and this difference increases with increasing gap distance or in other words the degree of nonuniformity of the electric field.

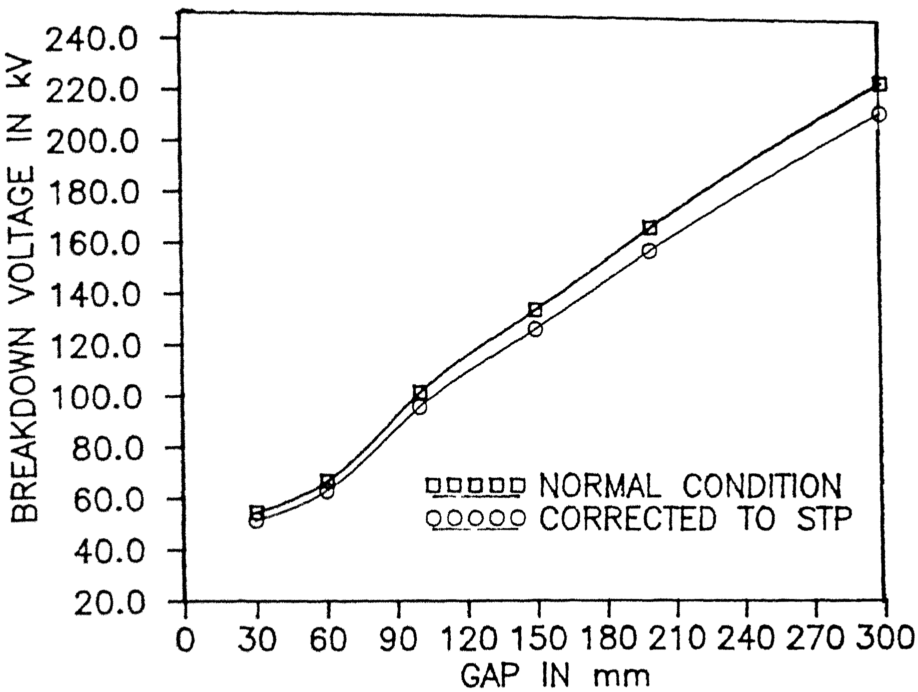


Fig 5.4(a): BREAKDOWN VOLTAGE (Ub 50) POSITIVE POLARITY AT NORMAL ATMOSPHERIC CONDITIONS AND AT STP CLEAN CONDITION OF ELECTRODE (ROD GAP 12 mm DIA)

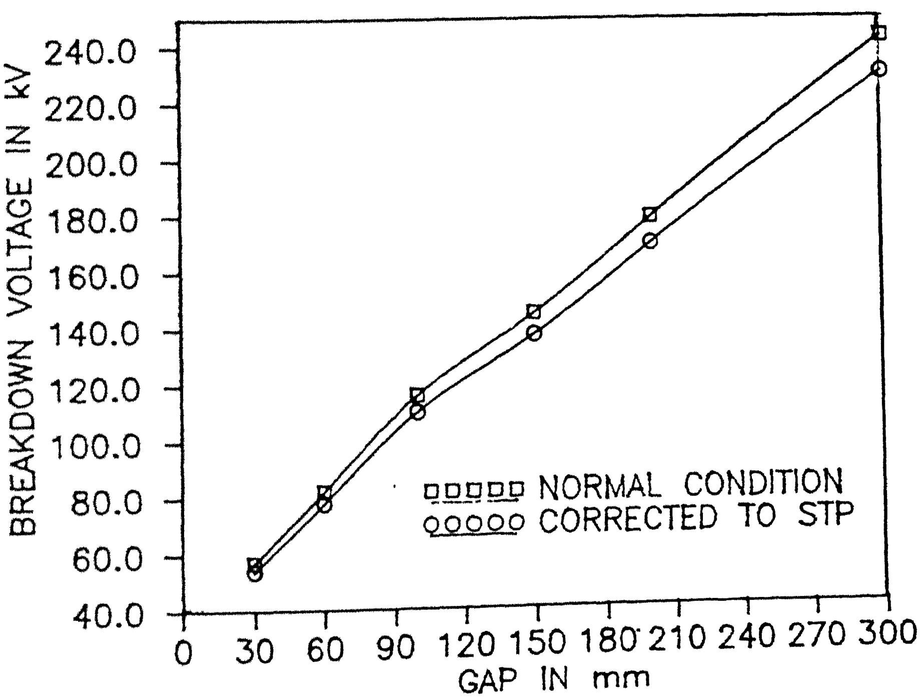


Fig 5.4(b):BREAKDOWN VOLTAGE (Ub 50) NEGATIVE POLARITY AT NORMAL ATMOSPHERIC CONDITIONS AND AT STP CLEAN CONDITION OF ELECTRODE (ROD GAP 12 mm DIA)

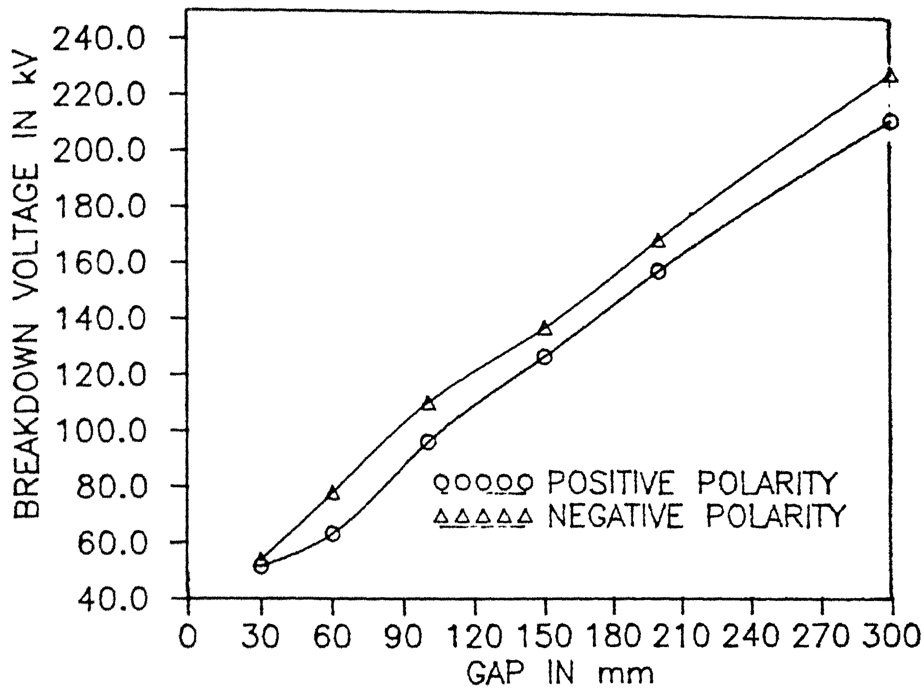


Fig 5.4(c): BREAKDOWN VOLTAGE (Ub 50)
FOR POSITIVE AND NEGATIVE POLARITY AT STP
CLEAN CONDITION OF ELECTRODE (ROD GAP 12 mm DIA)

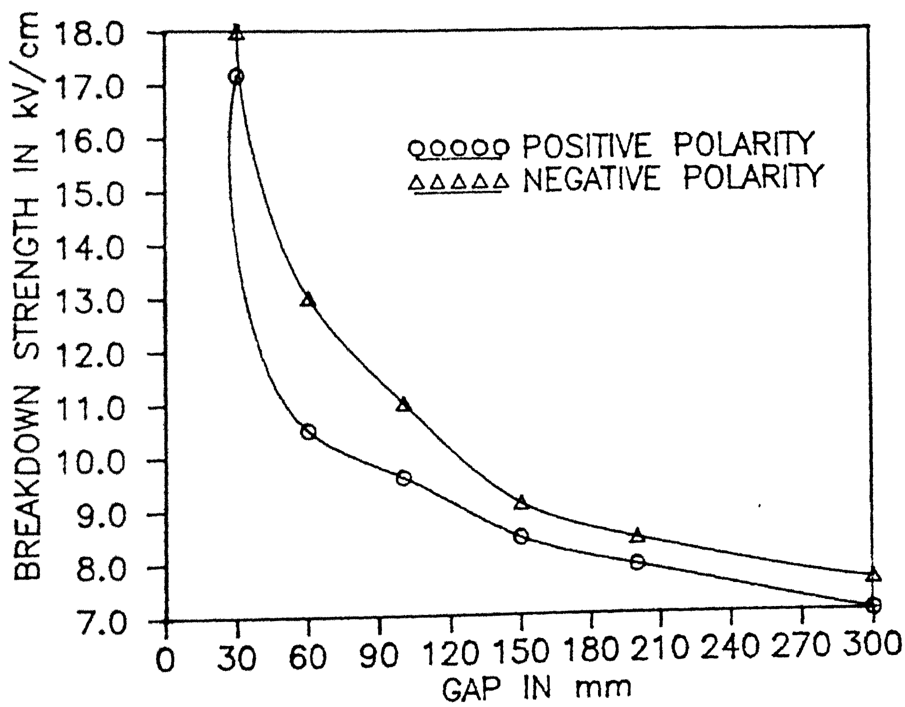


Fig 5.4(d) : BREAKDOWN STRENGTH OF AIR
FOR POSITIVE AND NEGATIVE POLARITY AT STP
CLEAN CONDITION OF ELECTRODE (ROD GAP 12 mm DIA)

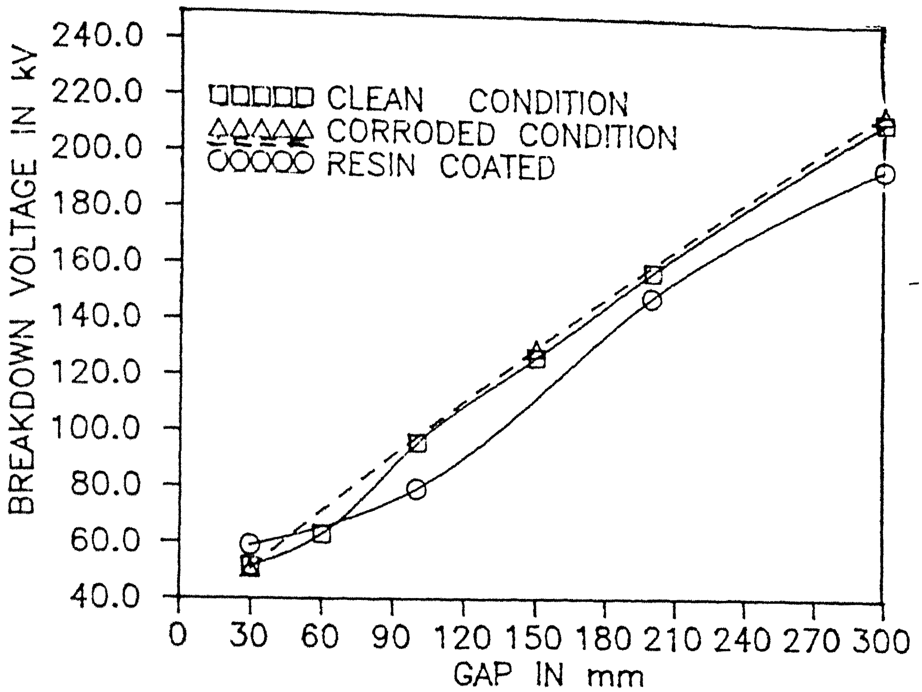


Fig 5.4(e): COMPARISION OF BREAKDOWN VOLTAGE POSITIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR ROD GAP 12 mm DIA CORRECTED TO STP CONDITIONS

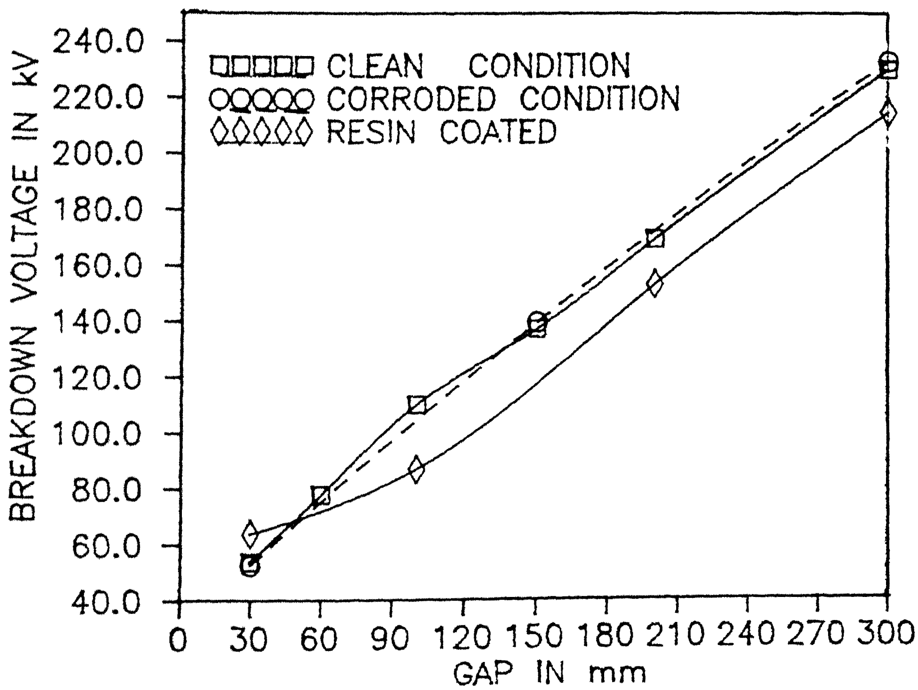


Fig 5.4(f): COMPARISION OF BREAKDOWN VOLTAGE NEGATIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR ROD GAP 12 mm DIA CORRECTED TO STP CONDITIONS

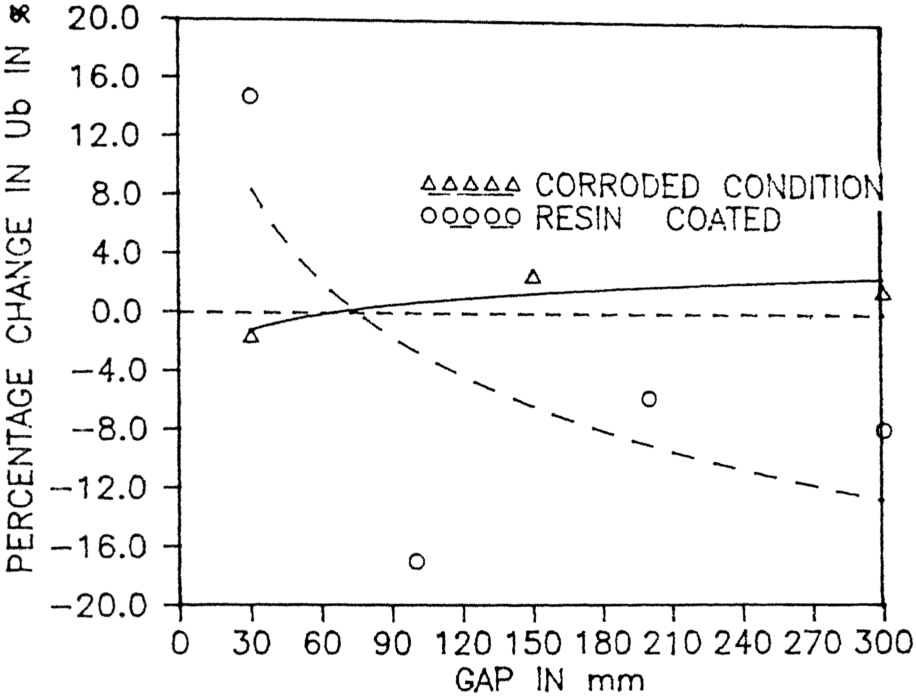


Fig 5.4(g): PERCENTAGE CHANGE IN BREAKDOWN VOLTAGE POSITIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE COMPARED TO CLEAN CONDITION FOR ROD GAP 12 mm DIA (STP CONDITIONS)

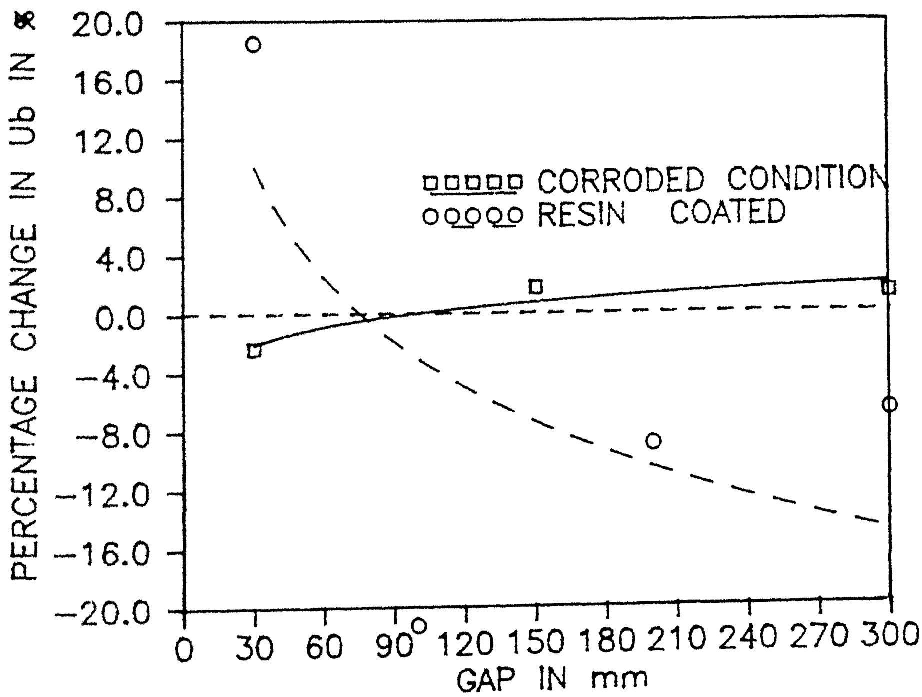


Fig 5.4(h):PERCENTAGE CHANGE IN BREAKDOWN VOLTAGE NEGATIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE COMPARED TO CLEAN CONDITION FOR ROD GAP 12 mm DIA (STP CONDITIONS)

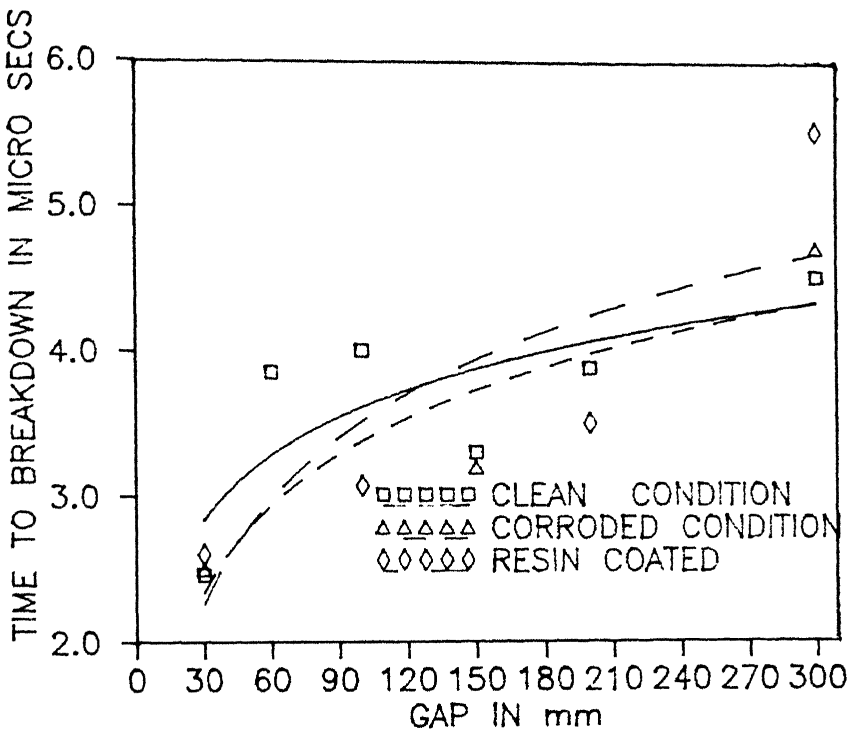


Fig 5.4(j): COMPARISION OF BREAKDOWN TIME FOR POSITIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR ROD GAP 12 mm DIA

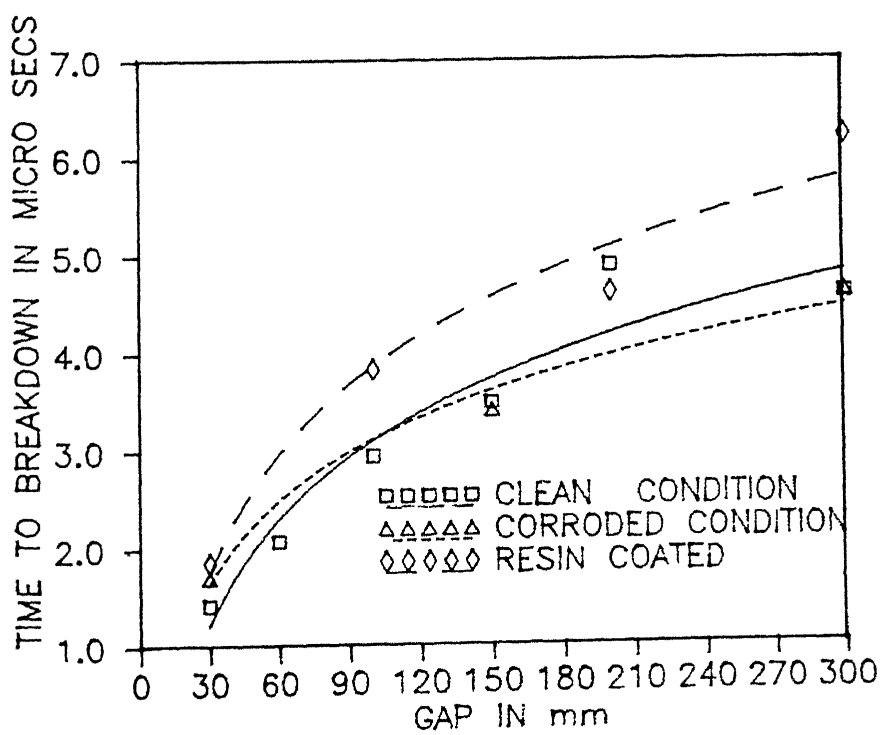


Fig 5.4(k) : COMPARISION OF BREAKDOWN TIME FOR NEGATIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR ROD GAP 12 mm DIA

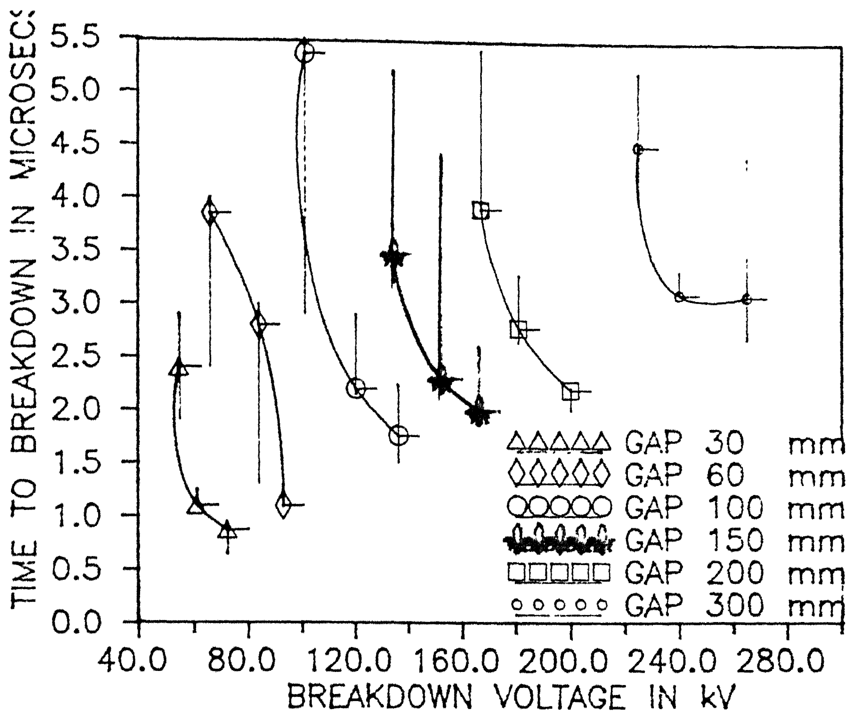


FIG 5.4(l): VOLT- TIME CHARACTERISTICS
POSITIVE POLARITY SPARK GAP DIA:12 mm
FOR GAP 30 mm TO 300 mm (CLEAN GAP CONDITIONS)

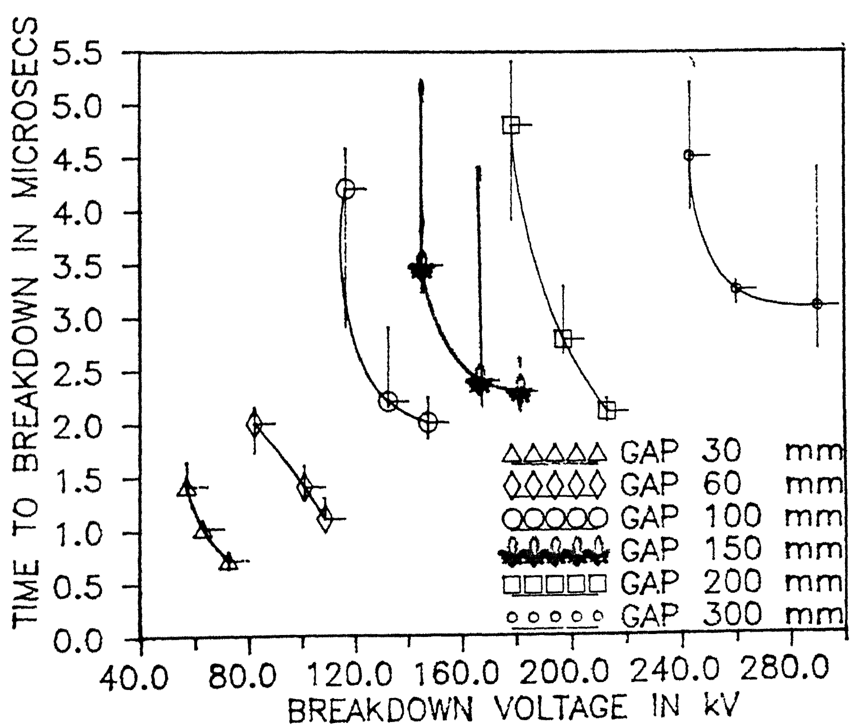


FIG 5.4(m): VOLT- TIME CHARACTERISTICS
NEGATIVE POLARITY SPARK GAP DIA:12 mm
FOR GAP 30 mm TO 300 mm (CLEAN GAP CONDITIONS)

Fig 5.4 (d) shows the variation of average breakdown strength of air E_{b+} and E_{b-} for positive and negative polarity li with gap distance d. The E_b varies from 18 kV/cm to 8.0 kV/cm for negative polarity li and 17 kV/cm to 7 kV/cm for positive polarity li when the gap distance is increased from 30 to 300 mm. The steep drop in E_b from gap distance of 30 mm to 120 mm indicates a rapid change in the degree of uniformity, η in this region representing a transition in the field characteristics. However it is not so rapid as in case of spark gap 1 due to larger diameter of the rod.

Figs 5.4 (e) and (f) show the variation of U_{bco} (Corroded) , U_{br} (resin coated) with gap d for both positive and negative polarity li. Figs 5.4 (g) and (h) show the percentage changes in U_b from the clean conditions. Due corrections have been applied for atmospheric conditions. The following can be concluded from these figures :-

(a) The breakdown voltage U_b for resin coated condition of electrode is higher than that for clean condition of electrode for small gap distance but gradually it falls below the clean condition values for longer gap distances. This trend is very similar to the one observed with spark gap 1 . However for the salt coated and partially corroded condition of the electrodes the breakdown voltage U_{bco} was measured higher (upto 4 %) than for the clean condition. This may be due to the fact that the corrosion layer is an integral part of the electrode surface unlike an external layer loosely applied on the electrode. Such a layer may not have provided the initiatory electrons. However, the presence of an insulating layer could have lead to higher breakdown voltages.

(b) On comparing the U_b for partially corroded and resin coated electrodes it can be seen that in case of both positive and negative polarity li the U_b for resin coated electrode is lower than that for partially corroded one. This difference however, reduces gradually with increasing gap distance, that is, reducing the degree of uniformity, η. Figs 5.4(j) and (k) compare the statistical time lag T_s for different conditions of the spark gap for both positive and negative polarity li. It can be observed that t_s in case of partially corroded conditions is measured slightly lower than that for clean or resin

coated conditions. This could be attributed to higher magnitudes of the breakdown voltage.

Figs 5.4 (l) and (m) show the volt-time characteristics of the spark gap for different gap distances for both positive and negative polarity li . Similar trends that were observed for spark gap 1 can be seen here also.

5.3.3 Investigations on Protective Spark Gap 3 (Sphere-Sphere Gap Diameter 40 mm)

This Spark gap was subjected to corrosion treatment by dissolving the galvanising zinc layer in sulphuric acid and then kept in a sea water salt fog chamber for 15 days. A thick layer of rust was formed on the surface of the electrodes.

Fig 5.5 (a) and 5.4 (b) give the variation of U_{b+} and U_{b-} with increasing gap distance d for both for positive and negative polarity li respectively for clean condition of electrode. Both measured and corrected values have been plotted showing the difference distinctly. The corrected U_b values are generally less than the measured ones. Fig 5.5 (c) compares the U_{b+} and U_{b-} values.It can be clearly seen that U_{b-} is greater than U_{b+} and this difference increases with increasing gap distance or in other words the degree of nonuniformity of the electric field.

Fig 5.5 (d) shows the variation of average breakdown strength of air E_{b+} and E_{b-} for positive and negative polarity li with gap distance d. The E_b varies from 23 kV/cm to 10 kV/cm for negative polarity li and 22 kV/cm to 7 kV/cm for positive polarity li when the gap length is increased from 30 mm to 330 mm. The drop in E_b with gap distance here is not so steep as in the case of the earlier two spark gaps indicating a more gradual transition of the field, due to larger diameter.

Figs 5.5 (e) and (f) show the variation of U_{bco} (Corroded) with gap distance d for both polarities of li. Figs 5.5 (g) and (h) show the percentage changes in U_b from the clean conditions. Due corrections have been applied for atmospheric conditions. It can be concluded from these figures that the breakdown voltage U_b for corroded condition of electrode is higher than that for clean condition of electrode for small gap distance but this difference gradually falls to approximately 2 % from the initial

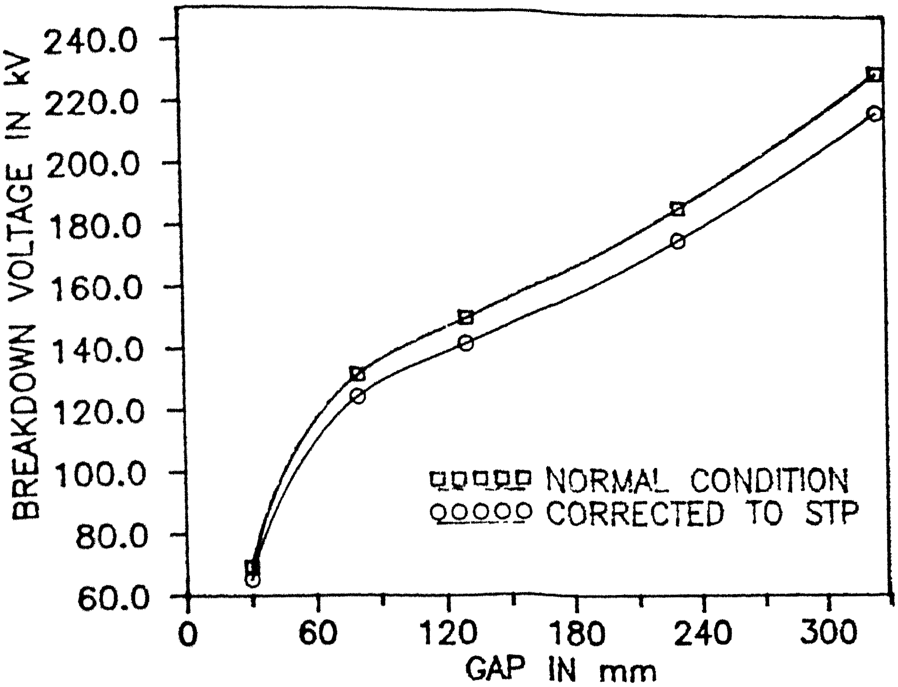


Fig 5.5(a):BREAKDOWN VOLTAGE (Ub 50) POSITIVE POLARITY AT NORMAL ATMOSPHERIC CONDITIONS AND AT STP CLEAN CONDITION OF ELECTRODE (SPARK GAP 40 mm DIA)

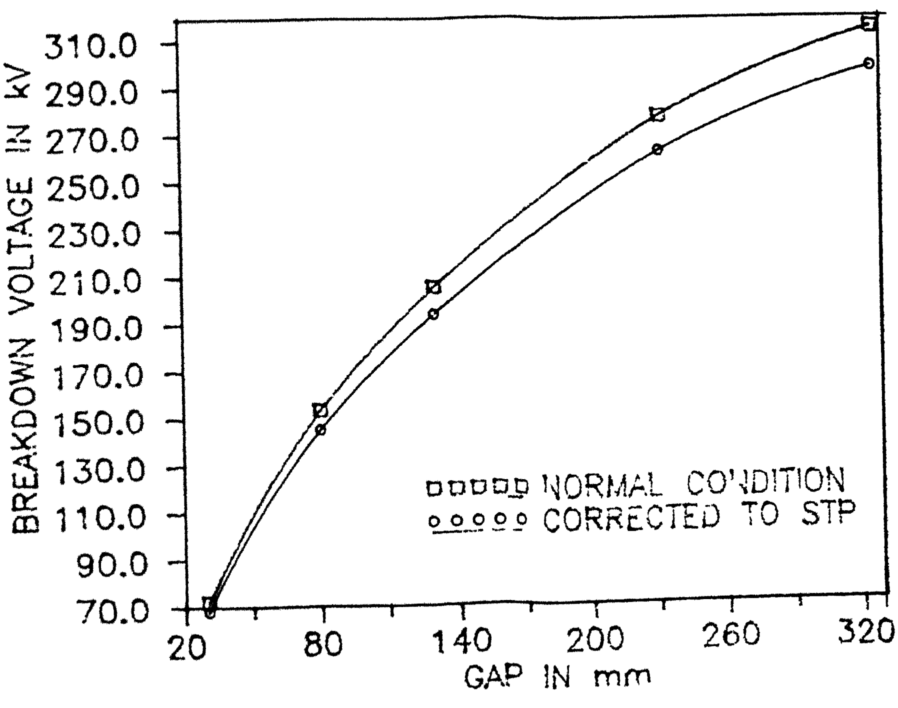


Fig 5.5(b):BREAKDOWN VOLTAGE (Ub 50) NEGATIVE POLARITY AT NORMAL ATMOSPHERIC CONDITIONS AND AT STP CLEAN CONDITION OF ELECTRODE (SPARK GAP 40 mm DIA)

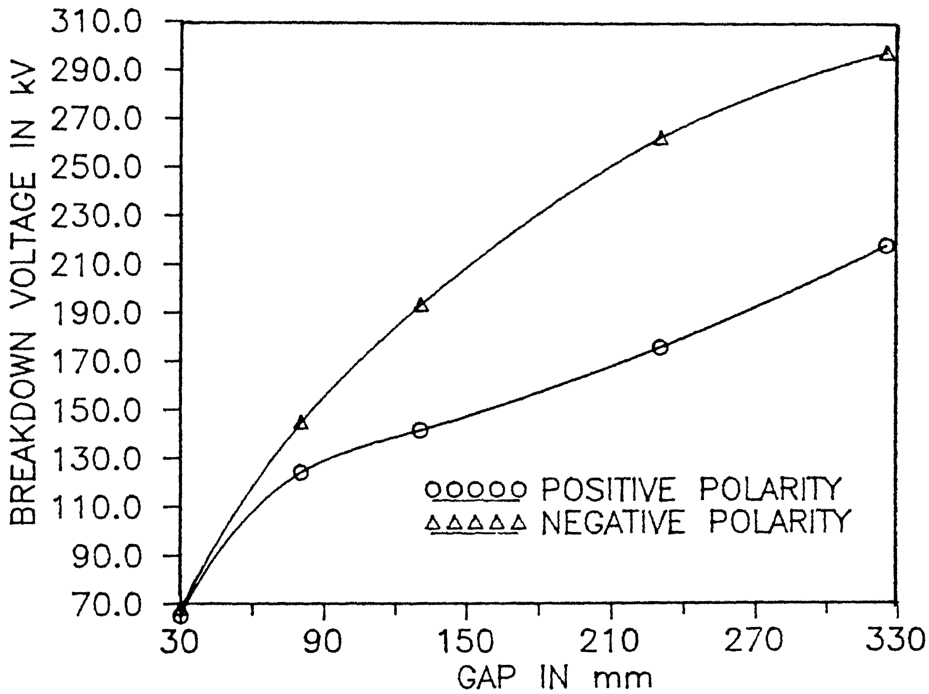


Fig 5.5(c): BREAKDOWN VOLTAGE (Ub 50)
FOR POSITIVE AND NEGATIVE POLARITY AT STP
CLEAN CONDITION OF ELECTRODE (SPARK GAP 40 mm DIA)

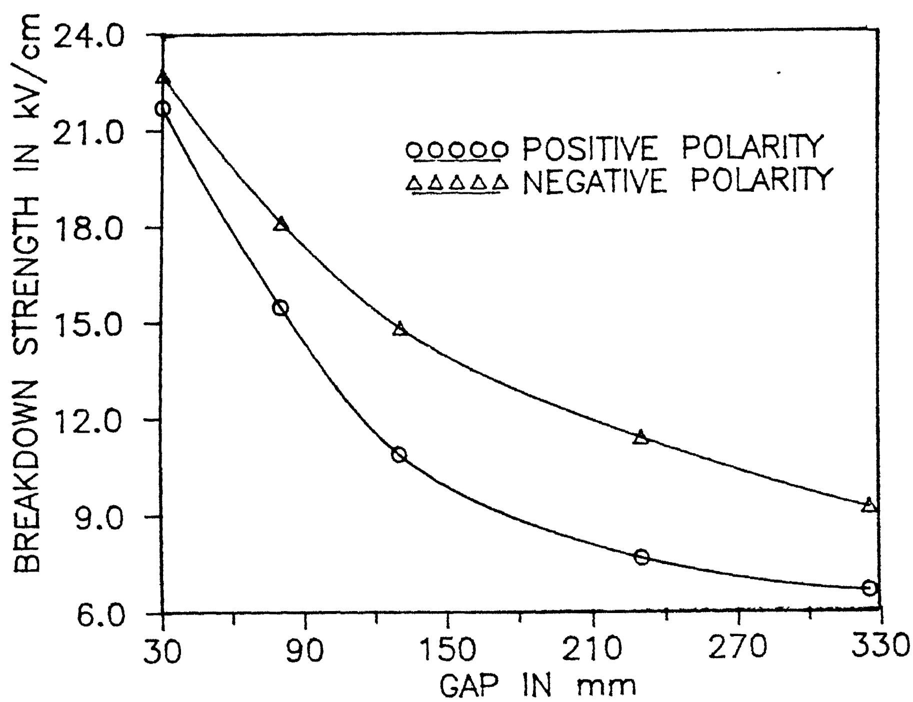


Fig 5.5(d) : BREAKDOWN STRENGTH OF AIR
FOR POSITIVE AND NEGATIVE POLARITY AT STP
CLEAN CONDITION OF ELECTRODE (SPARK GAP 40 mm DIA)

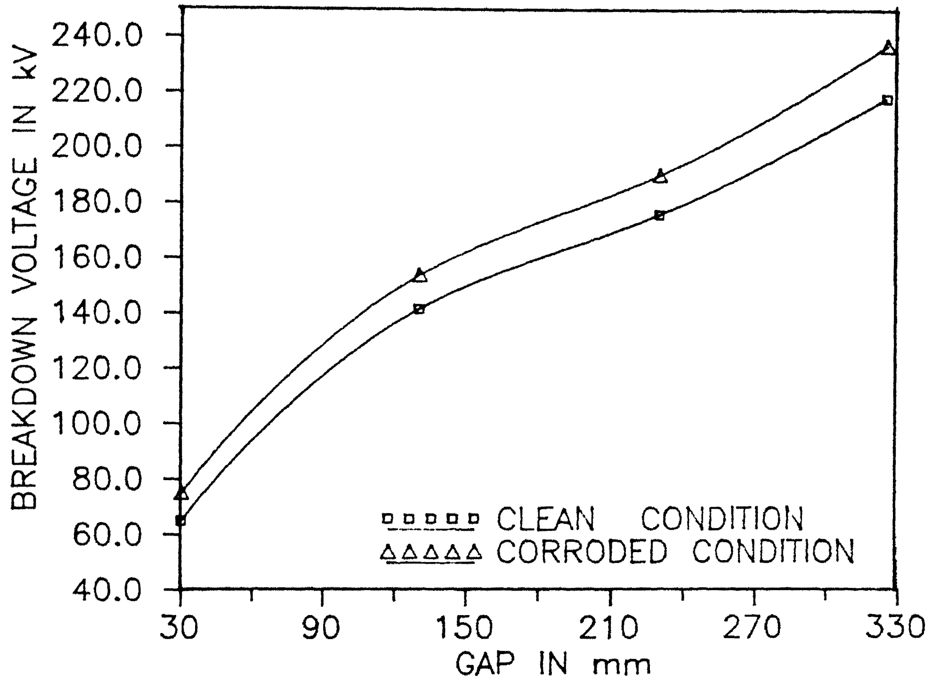


Fig 5.5(e) : COMPARISION OF BREAKDOWN VOLTAGE POSITIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR SPARK GAP 40 mm DIA CORRECTED TO STP CONDITIONS

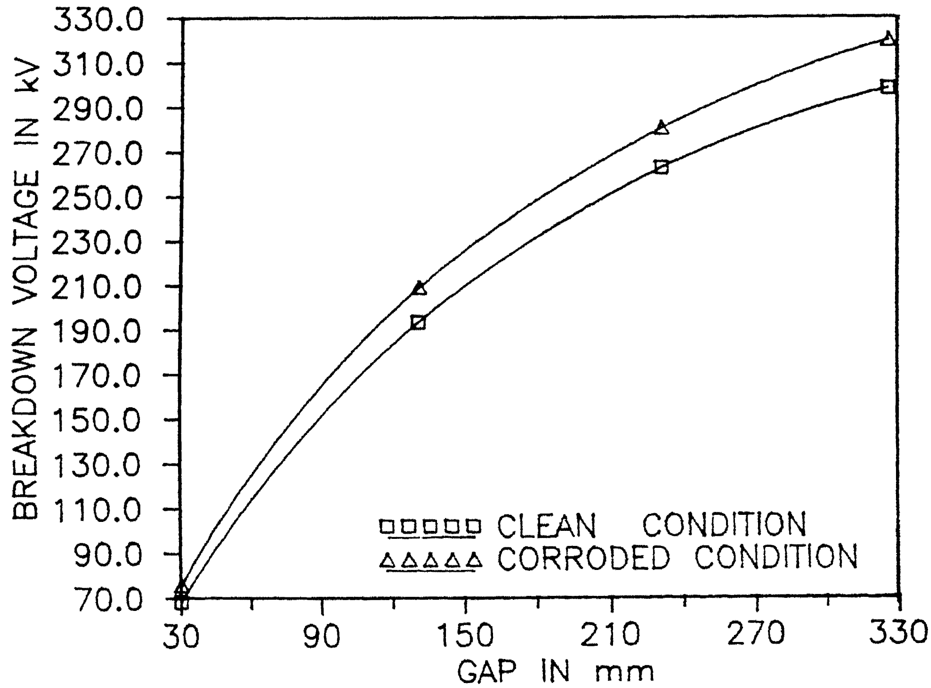


Fig 5.5(f): COMPARISION OF BREAKDOWN VOLTAGE NEGATIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR SPARK GAP 40 mm DIA CORRECTED TO STP CONDITIONS

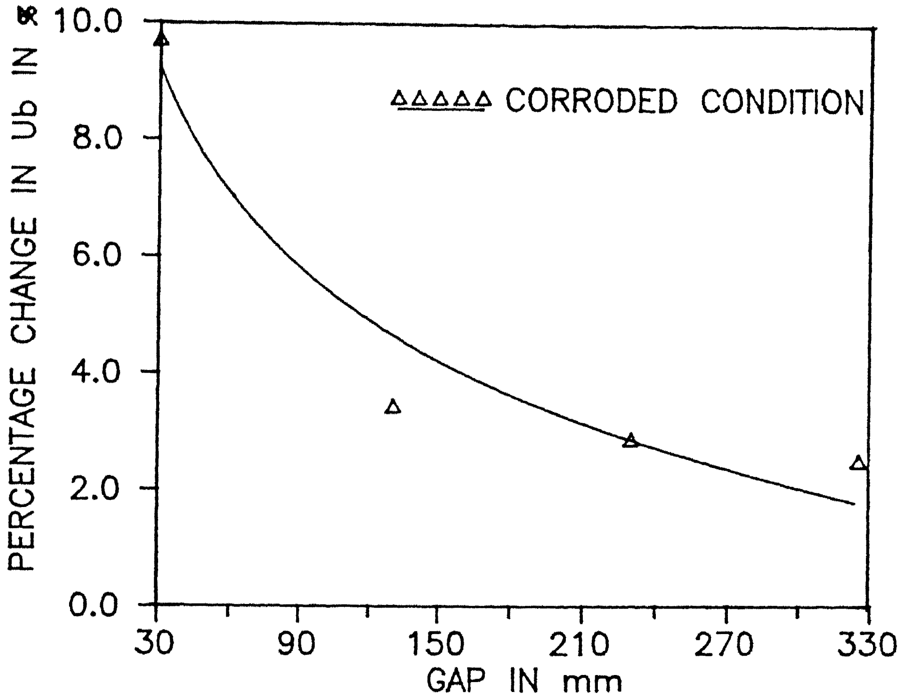


Fig 5.5(g): PERCENTAGE CHANGE IN BREAKDOWN VOLTAGE POSITIVE POLARITY FOR CORRODED CONDITION OF ELECTRODE COMPARED TO CLEAN CONDITION FOR SPARK GAP 40 mm DIA CORRECTED TO STP CONDITIONS

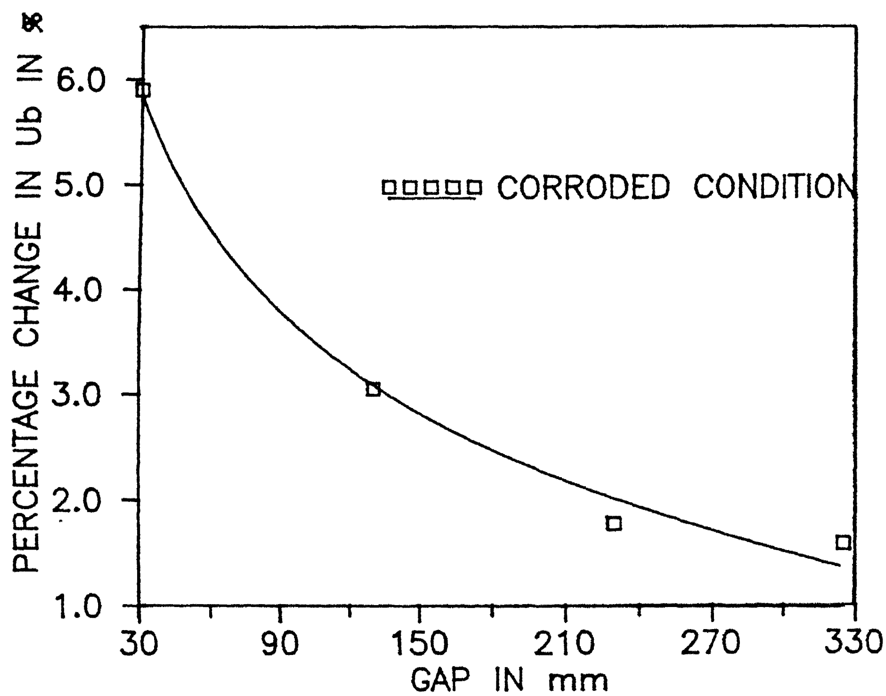


Fig 5.5(h): PERCENTAGE CHANGE IN BREAKDOWN VOLTAGE NEGATIVE POLARITY FOR CORRODED CONDITION OF ELECTRODE COMPARED TO CLEAN CONDITION FOR SPARK GAP 40 mm DIA CORRECTED TO STP CONDITIONS

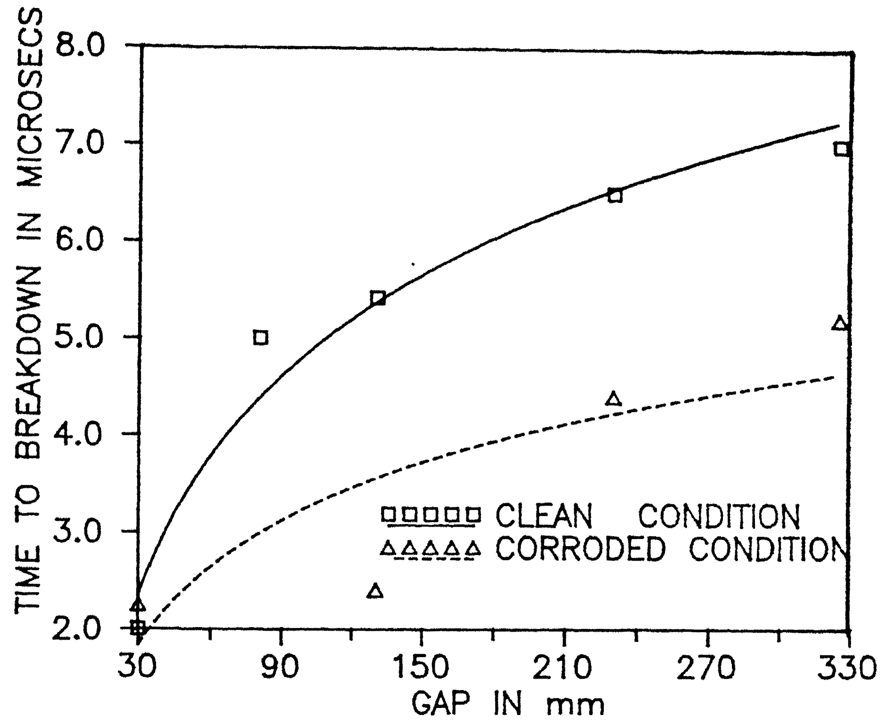


Fig 5.5(j): COMPARISION OF BREAKDOWN TIME FOR POSITIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR SPARK GAP 40 mm DIA

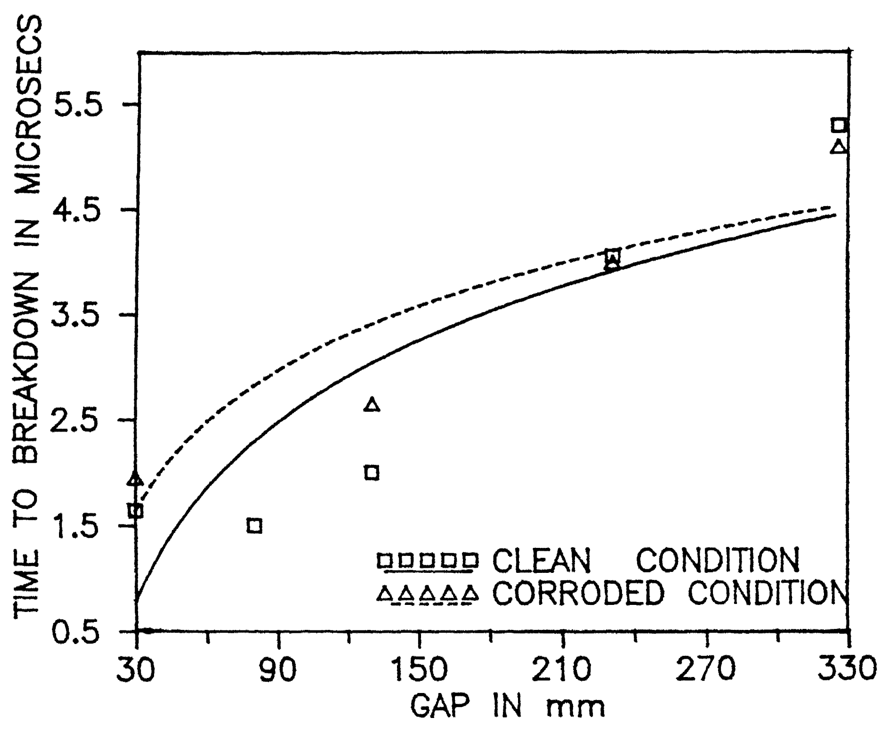


Fig 5.5(k) : COMPARISION OF BREAKDOWN TIME FOR NEGATIVE POLARITY FOR DIFFERENT CONDITIONS OF ELECTRODE FOR SPARK GAP 40 mm DIA

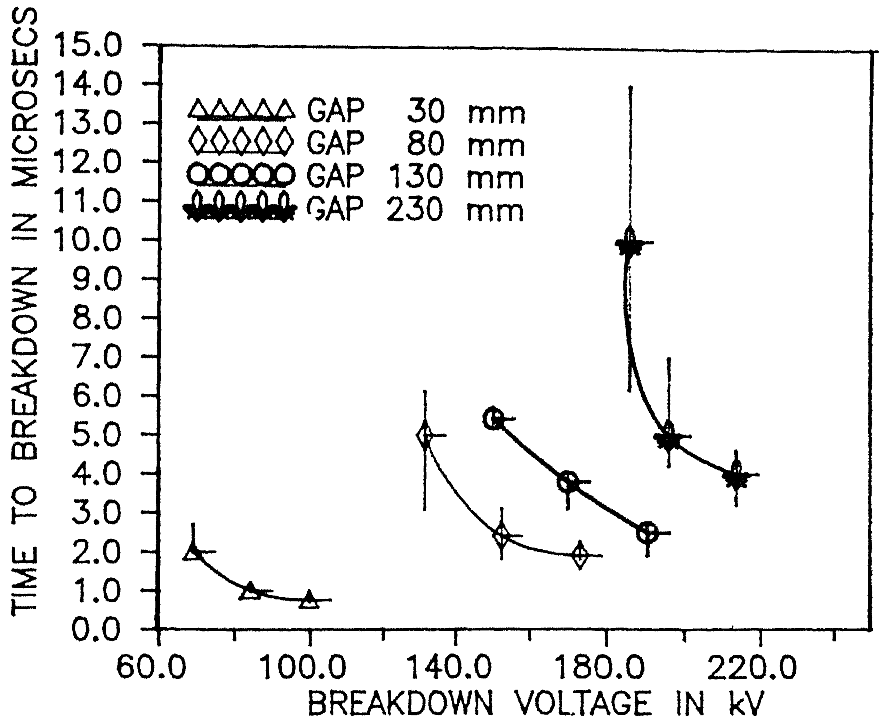


FIG 5.5(l): VOLT– TIME CHARACTERSTICS
POSITIVE POLARITY SPARK GAP DIA:40 mm
FOR GAP 30 mm TO 230 mm (CLEAN GAP CONDITIONS)

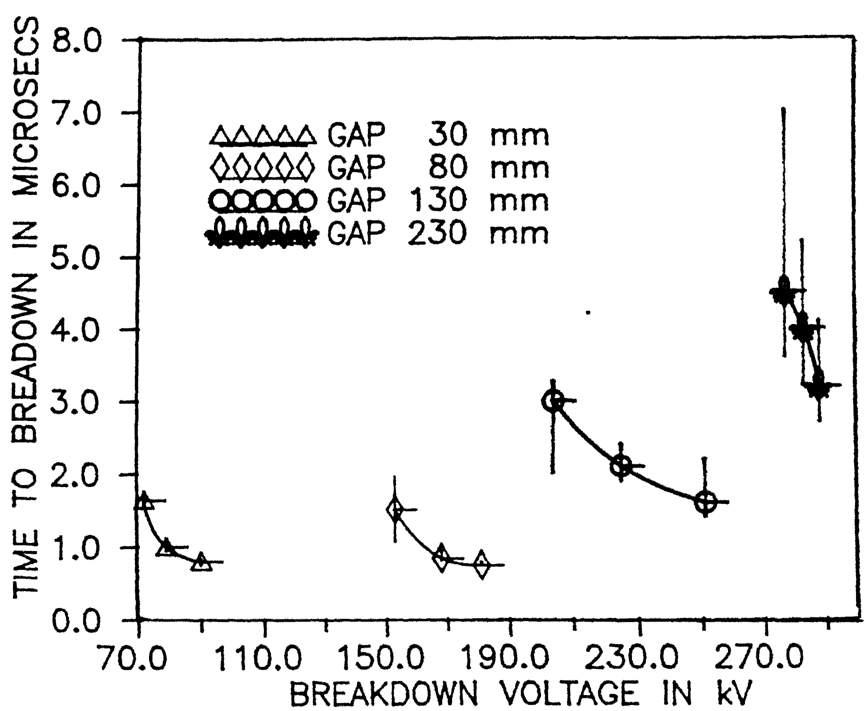


FIG 5.5(m) : VOLT– TIME CHARACTERSTICS
NEGATIVE POLARITY SPARK GAP DIA:40 mm
FOR GAP 30 mm TO 230 mm (CLEAN GAP CONDITIONS)

values of 6 to 10 % as gap is increased. This trend is very similar to the one observed for spark gap 2 .

Figs 5.5(j) and (k) compare the statistical time lag T_s for different conditions of the spark gap for both positive and negative polarity li. It can be observed that t_s in case of corroded condition is slightly lower than for clean or resin coated condition for positive polarity li but higher for negative polarity li.

Figs 5.5 (l) and (m) show the volt-time characteristics of the spark gap for different gap distances for both positive polarity li and negative polarity li . Similar trends that were observed for spark gap 1 and 2 can be seen here also.

CHAPTER 6

CONCLUSIONS

A comprehensive literature survey was conducted before the experimental investigations in this work. Although there are reports about recommending suitable shapes for the Air Terminal of a lightning conductor during the times of Franklin (Eighteen Century) /29/. They were based on statistics of natural lightning strikes. However, no such experimental work could be traced in the recent past.

6.1 The measurements conducted to study the effect of shape and size of the Air Terminal of the Lightning conductor, it can be observed that the average breakdown strength of Air was measured lowest for the Point electrode in case of long air gaps (3.76 - 5 3 m). However, for small air gap distances (15 - 35 cm) the lowest breakdown strength was measured for the Spiked electrode, followed closely by the Point electrode.

While investigating the time required for breakdown for both long as well as small gap distances, the lowest statistical time lag T_s was measured with the Point electrode. This was observed while measuring the U_{b-50} voltages as well as on applying a common level of breakdown voltage on all the electrodes separately. This indicates that the Point electrode will be preferred over other electrodes by a lightning strike. This was corroborated by the results of the Preferential Strike Tests also wherein the relative attractiveness of the Point electrode over other electrodes was experimentally established, both for small and long air gaps.

An early initiation and hence stronger return stroke from the Point electrode due to shorter statistical time lag was photographically confirmed (Photo 5).

The measurements with small gap distances (less than 36 cm), indicated the effect of the area of the electrode to some extent during the Preferential strike test. As the diameter of the similar shaped discs was increased from 25 to 100 mm. the li preferred to strike upon the larger diameter disc. This could be attributed to more availability of the initiatory electrons being ensured on larger area. However, this effect was

not significant beyond 100 mm disc (up to 255 mm dia).

On basis of the measured results the most suitable shape of the Air Terminal for the lightning conductors can be recommended to be the **Single Point Electrode.**

6.2 From the results of the investigations on the effect of Pollution and consequently that of corrosion on the performance of the Protective Spark Gaps in the range of gap distance of 30 mm to 330 mm, the following conclusions can be drawn.

(a) The breakdown voltage for both positive and negative polarity li under conditions polluted by thick dust layer (Kaolin)or a hard insulating layer (Resin) is lower than the breakdown voltage for clean condition of the electrode . This lowering of the breakdown voltage was measured up to 12 %. Longer the gap distance greater percentage reduction of U_b were observed. This lowering of the breakdown voltage withstand capability of the protective spark gap could lead to premature flashovers in cases of transient over voltages leading to temporary outages. However the equipment being protected by the protective spark gap would still remain protected. There is thus a need to clean the protective spark gaps regularly removing the insulating layer periodically.

(b) In case of corrosion caused over a prolonged period due to atmospheric condition aggravated by acid rains which dissolve the protective zinc layer, It was observed that the breakdown voltage for both positive and negative polarity li increased over the clean condition of the electrode. This increase was measured higher for small gap distances (6 - 10 %) but it reduced on increasing the gap distance to approximately 2 to 5 % for a maximum gap distance of 36 cm investigated.

(c) The increase of the voltage withstand level for corroded condition may lead to the malfunction of the protective spark gap in case of overvoltages generated by a lightning strike, thus causing excessive electric stress on the equipment being protected. The simultaneous lowering of the voltage withstand level of insulator strings or

bushings due to the pollution layer deposition on its surface can be at times dangerous. Therefore, it would be desirable to replace the corroded spark gap electrodes. Alternatively the tips of the spark gaps should be made of rust proof material like stainless steel, needing minimum of maintenance.

6.3 Recommendations for Further Work

The following recommendations for further work are suggested:-

(a) The performance of the Point electrode over other shapes of the Air terminal electrodes should be investigated using a very high speed camera to study the propagation and intensity of the return strokes generated from the various air terminals.

(b) The effect of pollution and corrosion on the performance of the Protective Spark Gap electrodes should be investigated for longer gap distances and also with Switching Impulse voltages.

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